ARL-MECH-ENG-REPORT-155 LEVEL (12) AR-001-792

AD A105211

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

MECHANICAL ENGINEERING REPORT 155

A VAPOUR CYCLE CABIN COOLING SYSTEM FOR THE SEA KING MK. 50 HELICOPTER

by

BRIAN REBBECHI

Approved for Public Release.

COPY No 16

FEBRUARY 1980

AR-001-792

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORIES

MECHANICAL ENGINEERING REPORT 155

(14) ARL/MECH ENG-155

(6)

A VAPOUR CYCLE CABIN COOLING SYSTEM FOR THE SEA KING MK. 50 HELICOPTER

by

(10) BRIAN REBBECHI

(11) Feb 79

(12) 59

SUMMARY

An experimental determination has been made of the design requirements for a cabin cooling system in the Sea King Mk. 50 helicopter. The purpose of this system is to bring the cabin environment in the helicopter to an acceptable level for effective crew performance. Cooling was provided by an experimental vapour cycle cooling system. Results of the trials have been used to formulate a heat transfer model of the cabin to enable prediction of required cooling capacity for extreme climatic conditions. A comparison, based on the trials results, is made between the performance attainable by a vapour cycle cooling system, and an air cycle system using the available engine bleed.

POSTAL ADDRESS: Chief Superintendent, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia.

DOCUMENT CONTROL DATA SHEET

Security classification of this page: Unclassified

1. Document Numbers
   (a) AR Number:
   AR-001-792
   (b) Document Series and Number:
   Mechanical Engineering Report 155
   (c) Report Number:
   ARL-Mech-Eng-Report-155

2. Security Classification
   (a) Complete document:
   Unclassified
   (b) Title in isolation:
   Unclassified
   (c) Summary in isolation:
   Unclassified

3. Title: A VAPOUR CYCLE CABIN COOLING SYSTEM FOR THE SEA KING Mk. 50 HELICOPTER

4. Personal Author:
   Rebbechi B.

5. Document Date:
   February 1980

6. Type of Report and Period Covered:

7. Corporate Author:
   Aeronautical Research Laboratories

8. Reference Numbers
   (a) Task: NAV 78/051
   (b) Sponsoring Agency:
   Department of Defence (Navy Office)

9. Cost Code: 43 4320

10. Imprint:
    Aeronautical Research Laboratories, Melbourne

11. Computer Program(s)
    (Title(s) and language(s)):

12. Release Limitations (of the document):
    Approved for Public Release

12.0. Overseas:	N.O.		P.R.	1	A		B		C		D		E	

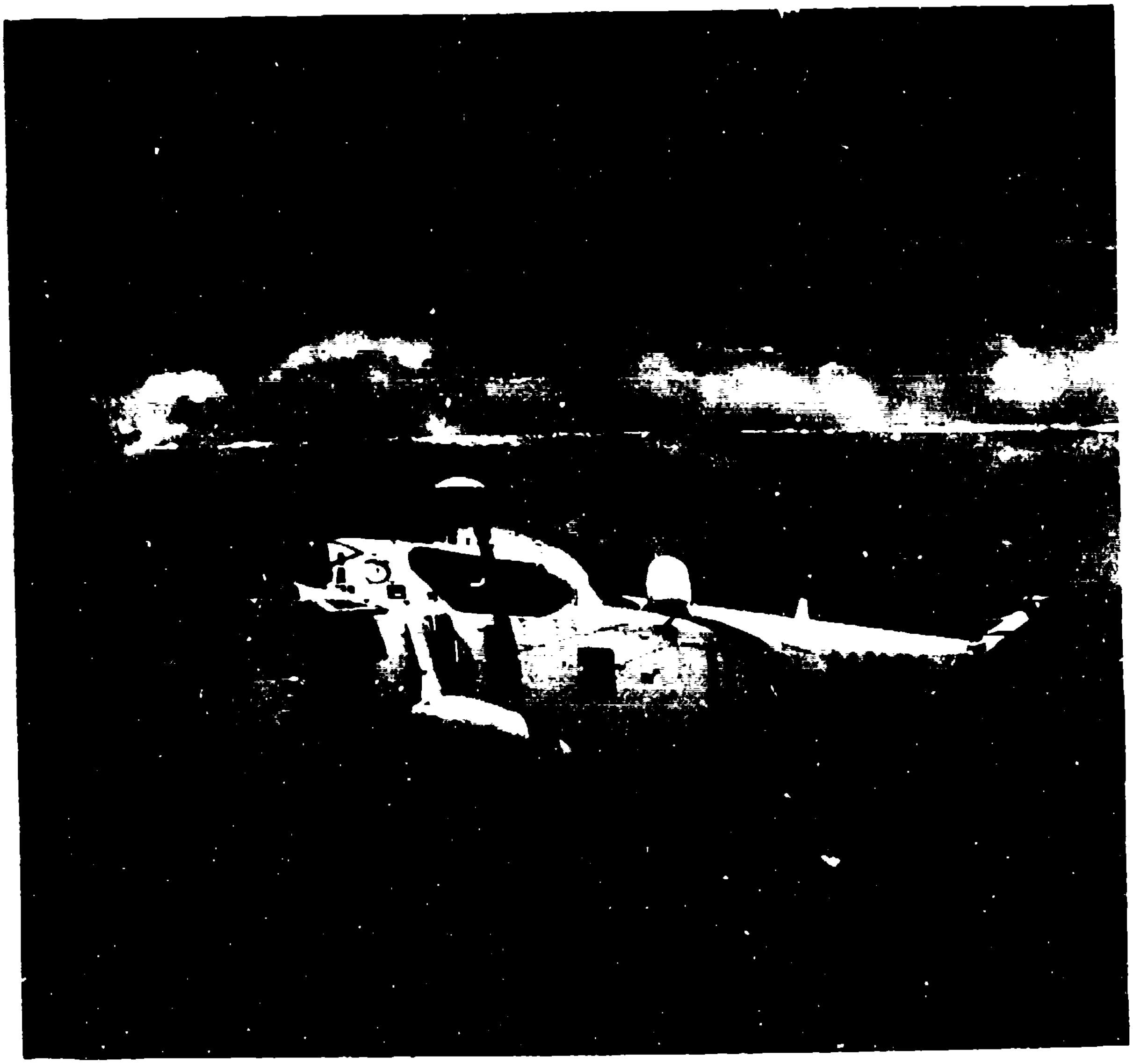
13. Announcement Limitations (of the information on this page):
    No Limitation

14. Descriptors:
    Helicopters
    Sea King Mk. 50
    Design criteria
    Aircraft cabins
    Cooling systems

15. Cosati Codes:
    1301
    0103

16. ABSTRACT

An experimental determination has been made of the design requirements for a cabin cooling system in the Sea King Mk. 50 helicopter. The purpose of this system is to bring the cabin environment in the helicopter to an acceptable level for effective crew performance. Cooling was provided by an experimental vapour cycle cooling system. Results of the trials have been used to formulate a heat transfer model of the cabin to enable prediction of required cooling capacity for extreme climatic conditions. A comparison, based on the trials results, is made between the performance attainable by a vapour cycle cooling system, and an air cycle system using the available engine bleed.



THE R.A.N. MK 50 SEA KING

CONTENTS

NOMENCLATURE

A	Effective area of fuselage for calculation of convective and radiative heat transfer (m^2)
A_1	Effective area of fuselage exposed to solar radiation (m^2)
A_2	Effective area of fuselage not exposed to solar radiation (m^2)
C_p	Specific heat of air (kJ/kg °C)
h_c	Convective heat transfer coefficient (fuselage skin to ambient air) (kW/m^2 °C)
h_{fg}	Latent heat of condensation of water (kJ/kg)
h_o	Overall cabin heat transfer coefficient (kW/°C)
h_r	Linearised radiation exchange coefficient (kW/m^2 °C)
h_w	Fuselage wall conductivity (exterior skin surface to interior air) (kW/m^2 °C)
KE_{out}	Kinetic energy per second of cooling air stream at outlet from airconditioning unit (kW)
m_e	Air mass flow through evaporator (kg/s)
m_f	Cabin ventilation air mass flow (kg/s)
m_{fa}	Cabin inlet air mass flow with air cycle cooling system (kg/s)
m_l	Leakage inflow of ambient air (kg/s)
m_r	Ram ventilating air mass flow (kg/s)
P_{h1}	Refrigerant pressure at outlet from compressor 1 (kPa)
P_{h2}	Refrigerant pressure at outlet from compressor 2 (kPa)
P_{l1}	Refrigerant pressure at entry to compressor 1 (kPa)
P_{l2}	Refrigerant pressure at entry to compressor 2 (kPa)
PE_{out}	Potential energy per second of cooling air stream at outlet from airconditioning unit (kW)
Q_c	Rate of heat removal from cabin by cooling unit (kW)
Q_e	Electrical equipment heat load on cabin interior (kW)
Q_{ec}	Cooling effect provided to electrical equipment (kW)
Q_{en}	Rate of heat input to cabin by engine and exhaust gas (kW)
Q_f	Fan heating of ventilation air (kW)
Q_{fa}	Heat load due to ventilation air (kW)
Q_h	Heating effect from cabin heater (kW)
Q_l	Cabin heat loading (kW)
Q_l	Rate of latent heat of condensation of moisture from air passing through evaporator (kW)
Q_m	Metabolic heat output rate of occupants (kW)

Q_s	Solar heat input to cabin transmitted through transparencies (kW)
Q_{si}	Incident solar radiation (kW/m²)
Q_w	Heat conduction through aircraft skin (kW)
δ_r	Decrease in humidity ratio of air (kg moisture/kg dry air)
T_a	Ambient dry bulb air temperature (°C)
T_c	Cabin mean air temperature (°C)
T_g	Cabin black globe temperature (°C)
T_i	Experimentally determined temperatures at location i (see Table 1) (°C)
T_{in}	Cabin inlet cooling air temperature with an air-cycle cooling system (°C)
T_{out}	Cabin outlet air temperature (°C)
T_{sky}	Effective sky temperature (°C)
T_{wb}	Psychrometric wet bulb temperature (°C)
T'_{wb}	Naturally convected wet bulb temperature (°C)
δT_c	Cabin temperature differential between ambient ($T_c - T_a$) (°C)
δT_e	Cooling air temperature rise through electronic equipment (°C)
δT_{sky}	Differential between ambient and effective sky temperature (°C)
δT_v	Temperature rise of air passing through cabin ventilating fan (°C)
WBGT	Wet bulb globe temperature (°C) (see definition, Section 2.2)
ϵ_s	Emissivity of fuselage upper surface at solar radiation wavelengths

1. INTRODUCTION

Since the introduction of the Sea King Mk. 50 helicopter into service in the Royal Australian Navy, flight crew of this aircraft have experienced problems with excessive cabin temperatures. This has led to the curtailment of operations and has greatly reduced the effectiveness of crew training in high ambient air temperatures.

Following discussion with the RAN, the Aeronautical Research Laboratories accepted the task of measuring the cabin environment, with regard to both vibration and temperature. The results of this environment survey are contained in the reports of Pavia and Edwards (1977) and Rebbechi and Edwards (1979); the latter gives the results of a four month temperature and humidity survey, when an instrumented Sea King was en route to the United Kingdom on HMAS *Melbourne*. The results from this survey confirm the severity of the cabin environment.

At the same time Rebbechi (1977) made a preliminary investigation, based on tests during a limited number of flights, of the sources of heat input to the cabin; from this an initial heat balance model of the cabin was derived. This investigation identified the major causes of cabin heating, and suggested methods of alleviating them; however, the thermal model showed that the only way to bring the cabin environment to an acceptable level was by the use of refrigerated air supplies. It was demonstrated that an air cycle cooling system using the maximum available engine compressor air bleed would not provide adequate cooling, and in addition would result in an unacceptable power loss. Further analysis indicated that an electrically powered vapour cycle cooling system, although likely to be heavier and bulkier, should give sufficient cabin cooling without excessive engine power loss.

The original thermal model of the cabin was based on a number of assumptions of unknown accuracy, and the operational problems of vapour cycle air-cooling systems for aircraft were less well known in Australia than those of air cycle systems. The RAN decided, therefore, to carry out flight tests of an experimental version of a vapour cycle air-cooling system, to

(*a*) establish the cooling capacity required,

(*b*) verify the cabin thermal model,

(*c*) evaluate the overall suitability of an electrically powered vapour cycle system, and

(*d*) evaluate cabin air distribution.

Following extensive bench testing of vapour cycle air-cooling systems based on automotive airconditioning components, an experimental cooling system for the Sea King was constructed at ARL during the latter half of 1978. This unit was not intended as a prototype, but only to accomplish the above objectives, and so provide a basis for the specification of a prototype/production installation for the RAN Sea King fleet.

The cooling unit was flight tested at HMAS *Albatross*, Nowra, New South Wales, during January-February 1979. This report describes the cooling unit, the results of the flight tests and the requirements of a production version.

2. THE CABIN COOLING PROBLEM

2.1 The External Environment

The external temperature environment has been taken to be that of the RAAF standard atmospheric environment, which specifies a maximum sea level temperature of 43°C, while the design maximum humidity limits have been taken from Av.P.970 (UK Ministry of Aviation 1960) and are shown in Figure 1. Av.P.970 gives a more detailed specification of humidity limits than the RAAF standard, although maximum moisture contents are identical. These temperatures and humidities are less severe than the world-wide Naval Air Environment of MIL-

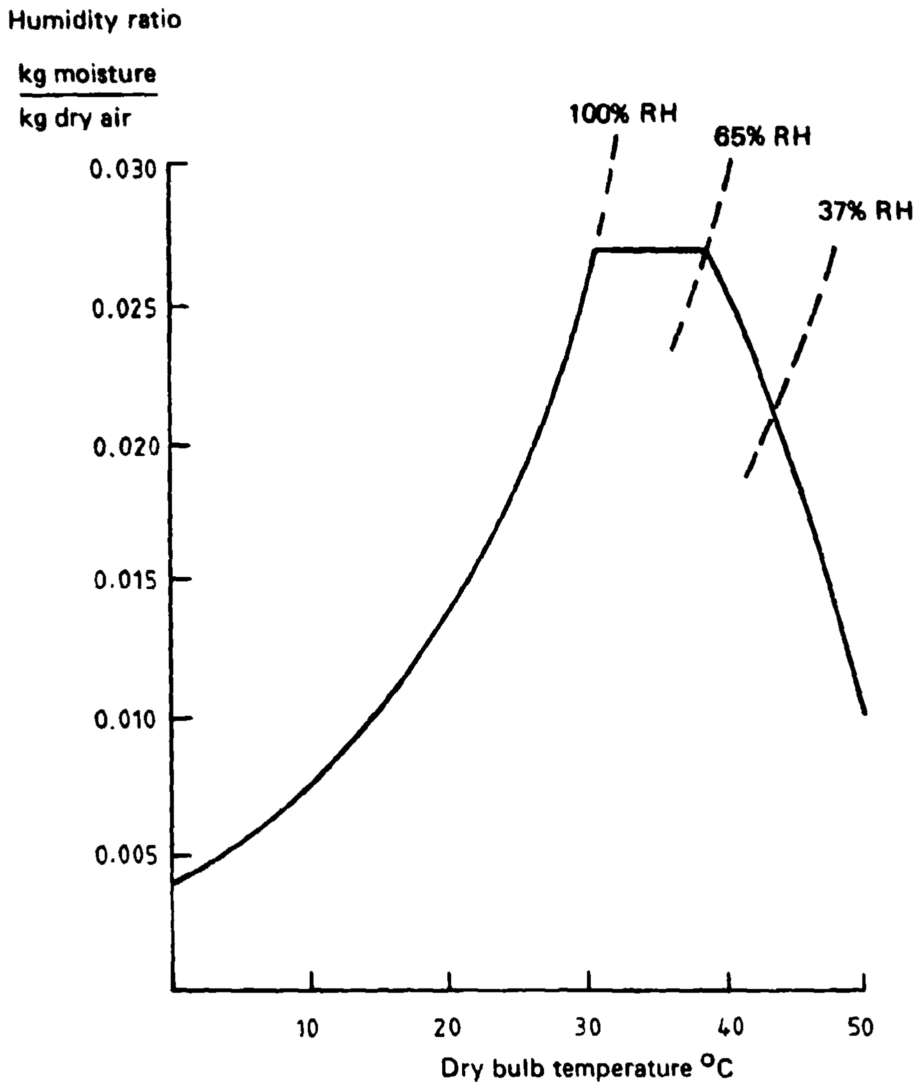


FIG. 1. DESIGN MAXIMUM HUMIDITY LIMIT RELATED TO TEMPERATURE FOR SEA-LEVEL. (REPRODUCED IN MODIFIED FORM FROM MINISTRY OF AVIATION, 1960.)

STD-210B, where the dry bulb temperature is 48°C, and the absolute humidity 0·030 kg moisture/kg dry air, for operations in 1% extreme conditions.*

2.2 The Required Cabin Environment

The wet bulb globe temperature (WBGT) is a thermal stress index which takes account of incident thermal radiation, ambient temperature and humidity. It is defined (Kerslake 1972) as

$$\mathrm{WBGT} = 0{\cdot}7T_{wb}+0{\cdot}3T_g, \tag{1}$$

where T_{wb} = psychrometric wet bulb temperature (°C)

T_g = temperature of a 150 mm black globe (°C).

An alternative expression, where the psychrometric wet bulb temperature is not available is,

$$\mathrm{WBGT} = 0{\cdot}7T'_{wb}+0{\cdot}1T_a+0{\cdot}2T_g, \tag{2}$$

where T'_{wb} is the temperature of a naturally convected wet bulb exposed to ambient radiation (°C), and T_a is the dry bulb temperature (°C). There is wide agreement that the WBGT should not exceed 28°C for effective aircrew performance—see, for example, the following references: RAAF Aircraft Research and Development Unit (1969, 1978); the RAAF Institute of Aviation Medicine (1976); and Nunneley *et al.* (1978).

This index level of 28° is not a "soft" criterion based on comfort—if it is exceeded, the foregoing references (and many others) assert that an impairment in crew efficiency will occur (an impairment that increases with flight duration), despite the high degree of motivation generally found in aircrew. The deleterious effects of an adverse environment can also be greater when learning than for routine tasks (Nunneley *et al.* 1978)—training is of course the primary peacetime role of the RAN Sea King.

2.3 The Known Present Cabin Environment

Measurements of the RAN Sea King cabin environment, without cooling (Rebbechi 1977; Rebbechi and Edwards 1979), have shown that the cabin temperature may be as high as 12°C above outside ambient air temperatures, the mean of a large number of readings being approximately 7·5°C, even with the limited ventilation afforded by opening the front vent windows. The cabin WBGT has been shown by Rebbechi and Edwards (1979) to reach 28°C at the quite moderate outside ambient temperature of 20°C. Operation of the Sea King in the climatic extremes referred to in Section 2.1 would be physiologically very hazardous to crew members.

It has been shown by Rebbechi (1977) that improvement to the cabin environment can be achieved by ducting large quantities of outside air through the cabin, and minimisation of cabin heating by avionics. However, neither of these palliatives, either singly or jointly, will bring the cabin environment in climatic extremes to an acceptable level for crew efficiency.

2.4 Cooling Load Predictions from the Initial Heat Transfer Model

The initial heat transfer model for the Sea King in forward flight is given by Rebbechi (1977) as

$$Q_l = \delta T_c[h_o+C_p(m_l+m_f+m_r)]-m_fC_p\delta T_v-Q_{en}, \tag{3}$$

where Q_l = cabin heat loading (metabolic+avionic+solar) (kW),

δT_c = temperature difference between outside air and cabin (T_c-T_a) (°C),

h_o = overall heat transfer coefficient (interior cabin air to outside ambient air) (kW/°C),

m_l = leakage inflow of ambient air (kg/s),

m_f = ventilation fan air mass flow (kg/s),

m_r = ram ventilating air mass flow (kg/s),

δT_v = temperature rise of air through ventilation fan (°C),

Q_{en} = heat input to cabin by engine and exhaust gas (kW),

C_p = specific heat of air (kJ/kg °C).

* The 1% extreme is the temperature (or humidity) exceeded for only 1% of the time (seven hours) in the hottest/most humid month of the year.

There are three unknowns in this equation which cannot easily be obtained from flight test data. The first, h_o, was estimated theoretically to be 0·17 kW/°C. The value of m_l was estimated at 0·11 kg/s. Using this data, the value of Q_{en} was estimated at 0·98 kW.

Considering now the cooling effect required to bring the cabin to a particular temperature, Equation (3) will need to be modified in the following manner:

(*a*) the addition of a cooling effect term Q_c (kW);

(*b*) deletion of the air leakage term m_l (one would assume considerable effort to be made to reduce excess ambient air inflows, if cabin is to be cooled);

(*c*) deletion of the ram air ventilation term m_r;

(*d*) reduction or elimination of the δT_v term, consequent on substitution of a smaller, more efficient ventilation fan;

(*e*) addition of a term involving latent heat of condensation of moisture in ventilation air.

The heat balance, Equation (3), becomes then

$$Q_c = (T_a - T_c)(h_o + C_p m_l) + Q_i + Q_{en} + Q_l, \qquad (4)$$

where Q_l is the additional heat load due to condensation of moisture in ventilation air. For a typical mission in full solar radiation,

$$Q_i = Q_s + Q_m + Q_e,$$

where Q_s = 2·0 kW (solar input),
Q_m = 0·5 kW (four persons),
Q_e = electrical heat (input from avionics may range between 0·5 and 3·0 kW).

Then, for an outside ambient air temperature of 43°C and a relative humidity of 37%, the cabin cooling load, as a function of cabin WBGT and dry bulb temperature can be plotted as in Figure 2. Further details of the calculations to arrive at this figure are given in Appendix 1. From this figure it can be seen that where the electrical load is 3·0 kW, the estimated cooling requirement is 9·0 kW, if the cabin WBGT is to be below 28°C.

3. EXPERIMENTAL EQUIPMENT FOR AIRCONDITIONING TRIALS

3.1 The ARL Airconditioning Unit

The airconditioning unit was designed and constructed at ARL. It was intended only as a trials unit to be used for limited and closely monitored flight trials. For this reason little regard was given to the size and weight of the unit.* The selection of components for the cooling unit was based on the results of bench testing of automotive type airconditioning components at ARL during November 1977–July 1978.

The airconditioning unit is pictured (with cover removed) in Figure 3; the component layout is indicated in Figure 4, and a schematic layout of the system is given in Figure 5. To obtain the cooling effect required it was found that two refrigerant compressors were necessary, and to avoid possible problems of oil transfer from one compressor to the other it was decided that the unit would contain two separate cooling systems. The motors were 200 V, 400 Hz, 6 h.p. Lucas motors, type LK1616 with SP7 gearboxes. The complete unit was designed to be contained in the one box, to simplify test and installation. This configuration would, however, be quite unacceptable in a production version, both because of the intrusion on cabin space and the rearward shift of aircraft centre of gravity.

The evaporator and condenser fans were 270 mm diameter, backward curved centrifugal type. Backward curved blades were considered essential for the condenser fan where ram effects could change the fan pressure differential in some flight conditions (see inlet and outlet ducting in Figure 7). The use of a forward-curved fan in this situation could result in motor overloading.

The refrigerant was Freon 12 (R12). This is one of the four refrigerants commonly used in aircraft, and was chosen for the following reasons:

---

* It is envisaged that a production unit would be very much lighter and smaller. Conklin (1964) describes the performance of a vapour cooling cycle unit in a VH-3A helicopter (a Presidential version of the Sikorsky SH-3, from which the Westland Sea King was derived), where the system weight was 73 kg, and system components were situated outside the cockpit–cabin area.

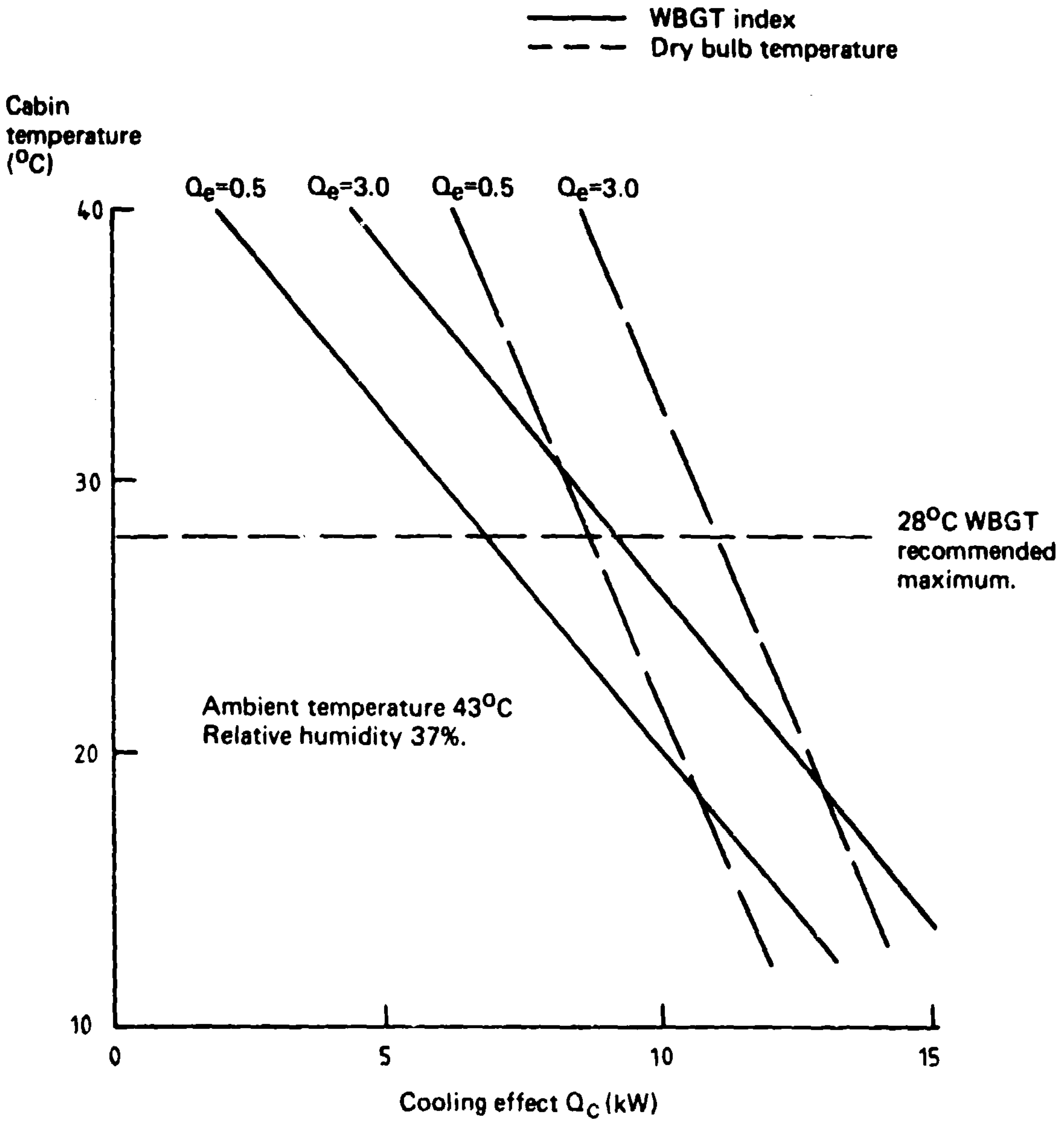


FIG. 2. COOLING LOAD PREDICTIONS FROM INITIAL HEAT TRANSFER MODEL.

(*a*) suitable for use in positive displacement compressors;
(*b*) non-toxic;
(*c*) non-flammable.

3.2 Installation in the Aircraft

The installation of the ARL cooling unit was carried out by the RAN Aircraft Maintenance and Flight Trials Unit (AMAFTU) at HMAS *Albatross*, Nowra. The airconditioning unit installation is pictured in Figure 6. The cooling air supplies for the condenser were taken in through a modified door (see Fig. 7) and returned via the outlet, situated above the inlet. Shielding, as in Figure 7, was attached around the outlet to prevent spillage of hot outlet air to the inlet, and to prevent an adverse pressure differential developing in flight between the inlet and outlet, which would reduce condenser air flow. The 200 V, 400 Hz, three-phase electrical power was taken from the aircraft non-essential contactor located in the nose compartment. As power to the non-essential contactor is disconnected in the event of a failure of either of the generators, the extra electrical load of the cooling unit would not endanger the flight systems. Two interior views of the installed unit are given in Figures 8 and 9.

3.3 Ducting of Cooling Air

Ducting was installed in the aircraft to bring the refrigerated air supplies into close proximity to the four crew members—namely pilot, co-pilot, sonar operator and navigator.

The ducting layout is sketched in Figure 10. The air outlets directed air towards the torso region of the crew in the case of the two rear crew members (see Figs 11 and 12), and towards both the torso and head region in the case of the two pilots (see Figs 13 and 14). The tape shown on the air outlets in Figures 11 and 12 was a temporary expedient to regulate the airflows from these outlets, and was not intended to be indicative of the configuration for a prototype/production installation.

The head region cooling was provided to compensate for the direct solar heat loading, which is absent in the case of the two rear crew. Figure 15 shows the air distribution box mounted above and behind the pilot seats. An additional piece of trunking is shown projecting downwards from the box and distributing air into the general cockpit area. Figure 16 shows the two 150 mm ducts which ran foward from the airconditioning unit to the distribution box; Figure 17 shows the attachment of the ducting at the airconditioning unit outlet.

The airflow distribution in the cabin was arranged so that the air mass flow to the front cockpit was twice that supplied to the two rearmost crew members. This differential was to provide for the difference in heat loadings in the two areas and to provide an equivalent environment for all four crew members. The basis for this estimate of relative heat loadings was the earlier work of Rebbechi (1977).

The total cooling air mass flow was 0·680 kg/s, giving rise to air velocities at the outlets of approximately 13 m/s; this velocity was, however, diminished by eddy diffusion to approximately 3·6 m/s immediately adjacent to the crew. This velocity is higher than generally accepted values for crew compartments, for example MIL-E-18927D prescribes a limit to air velocity at head level of 1 m/s, and Hughes (1968) suggests that an air velocity of 3 m/s is acceptable for areas other than the face and exposed areas of the body.

3.4 Instrumentation

3.4.1 Air Temperature and Humidity

Air temperatures were measured by NiCr/NiAl (type K) thermocouples. Humidity was estimated from wet bulb temperatures, measured by NiCr/NiAl thermocouples, using ARL-built apparatus as in Figure 18. The cabin air temperature was measured at five locations—between sonar and radar consoles (Fig. 18), behind pilot's seat (Fig. 19), just aft of the "broom cupboard" (Fig. 20) and at two points just forward of the sonar and radar consoles. Readings from the point aft of the "broom cupboard" were found to be higher than in the surrounding

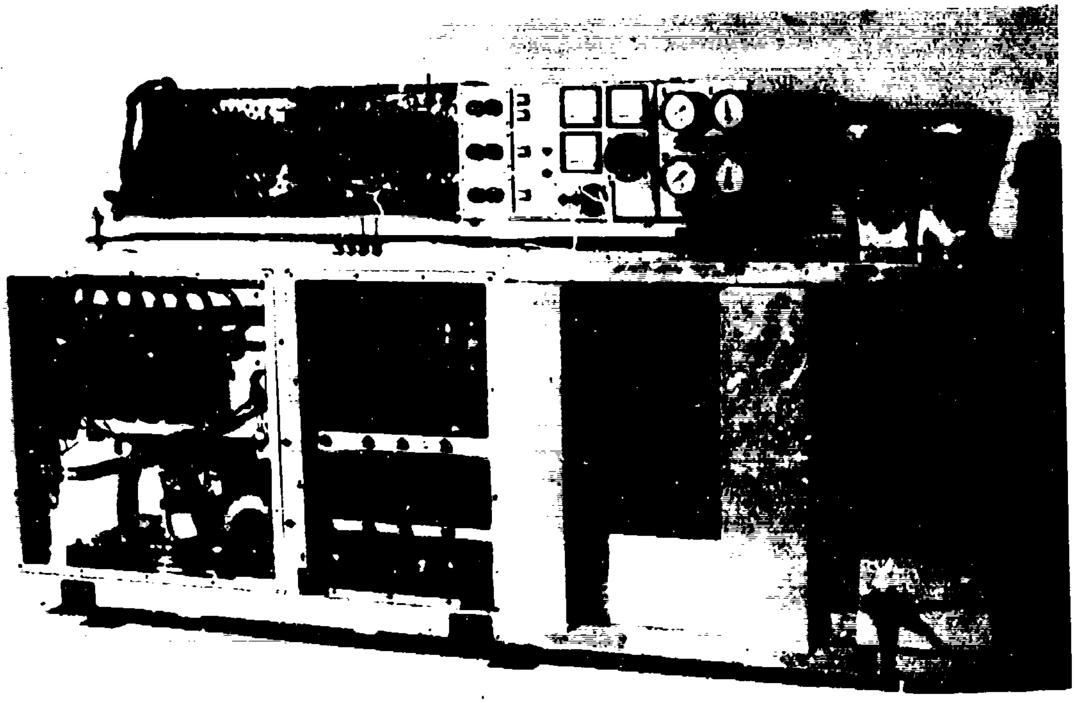


FIG. 3. THE ARL COOLING UNIT.

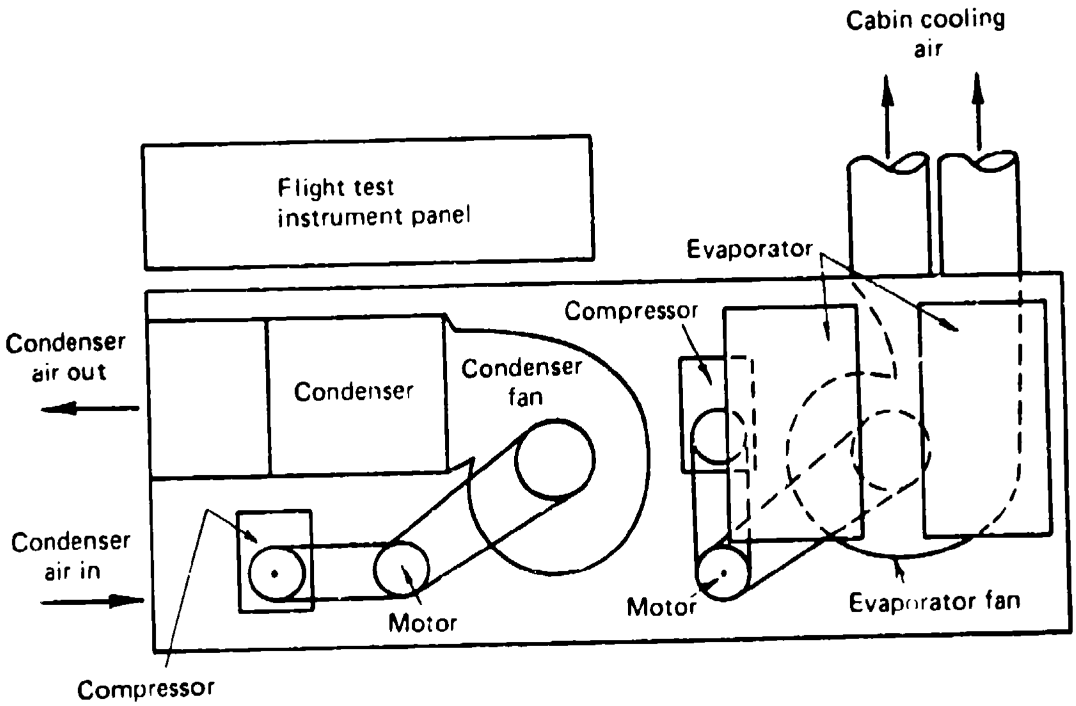


FIG. 4. COOLING SYSTEM LAYOUT

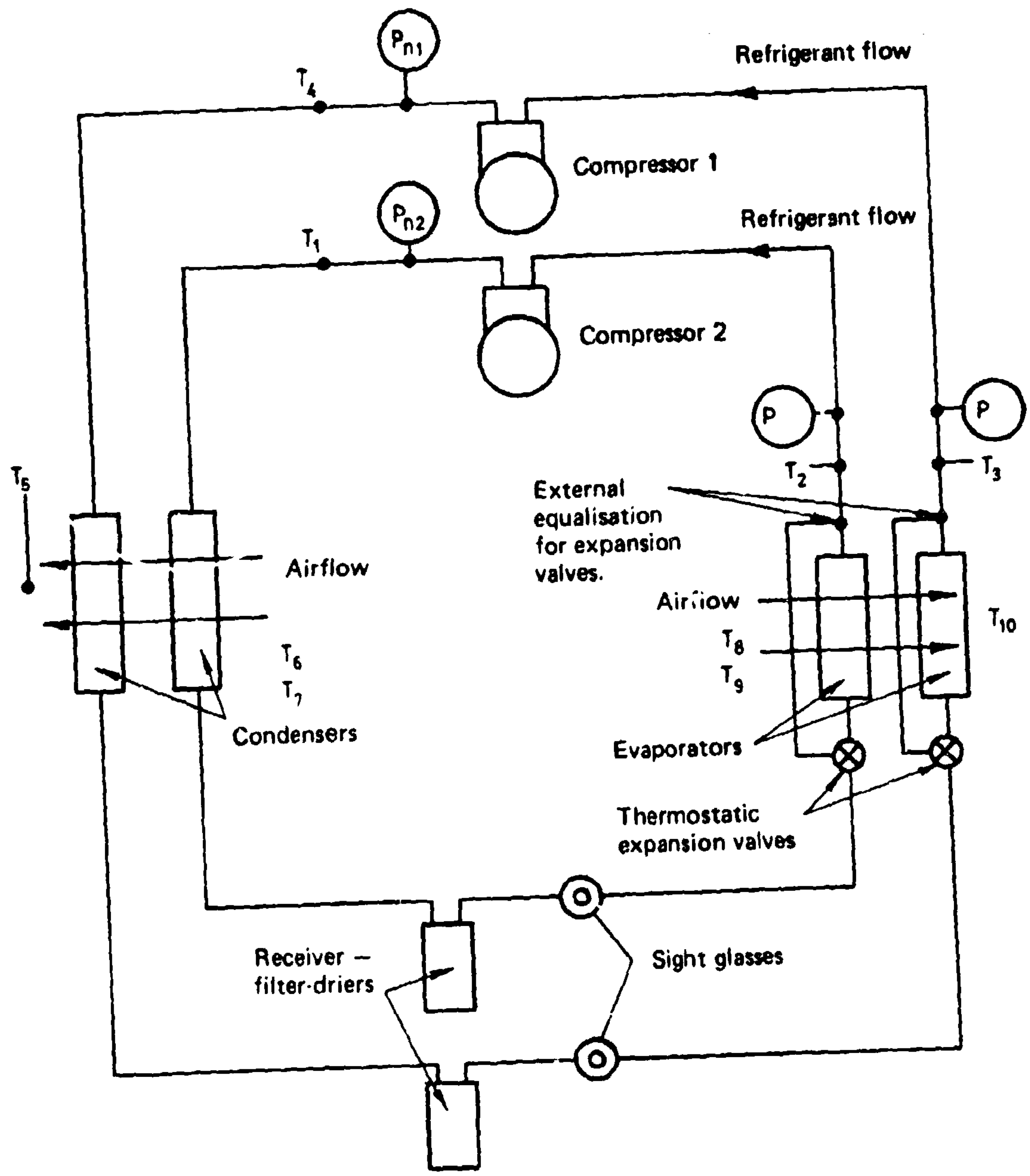


FIG. 5. COOLING SYSTEM SCHEMATIC.

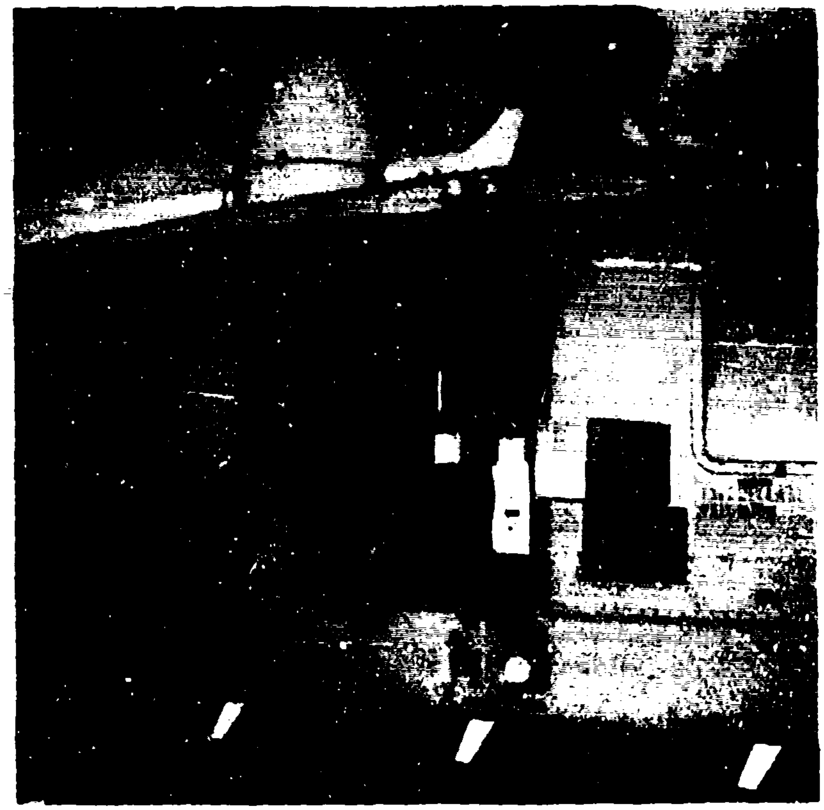


FIG. 6. COOLING UNIT INSTALLED IN AIRCRAFT

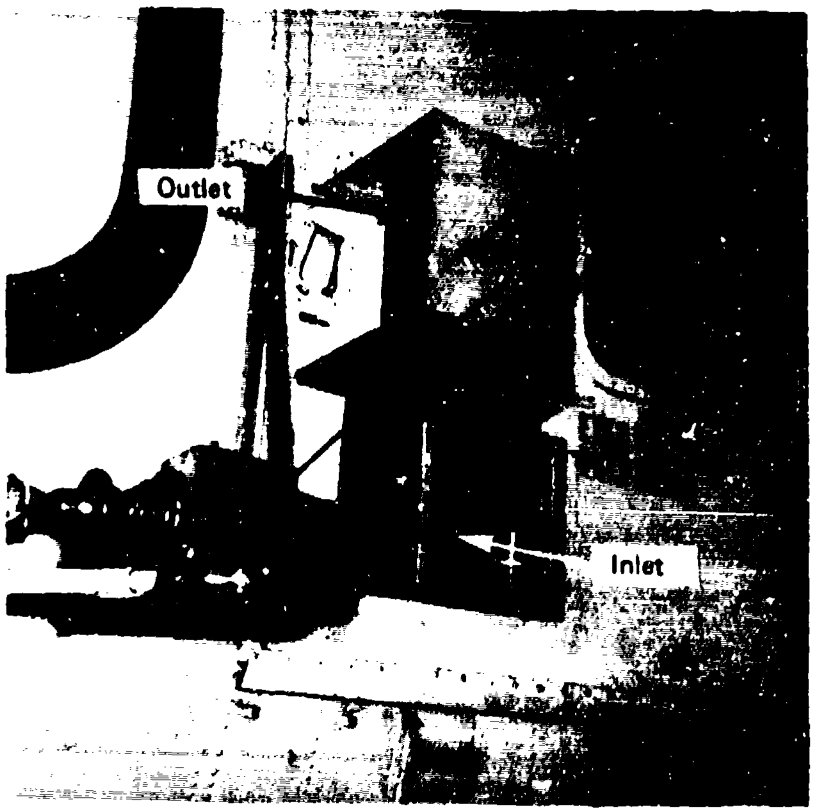


FIG. 7. CONDENSER COOLING AIR INLET AND OUTLET

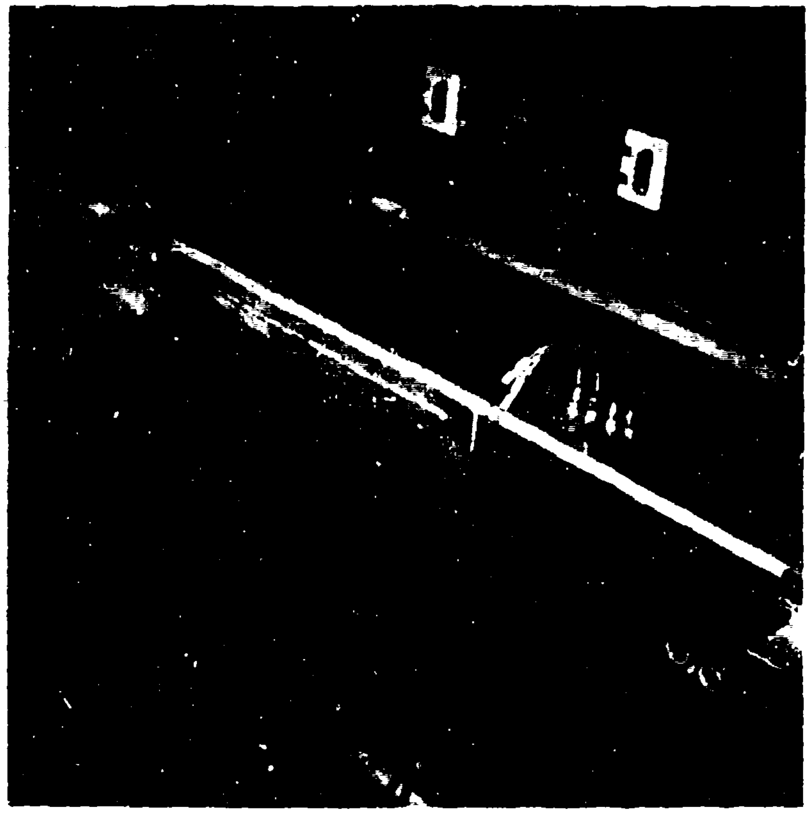


FIG. 8. COOLING UNIT IN AIRCRAFT

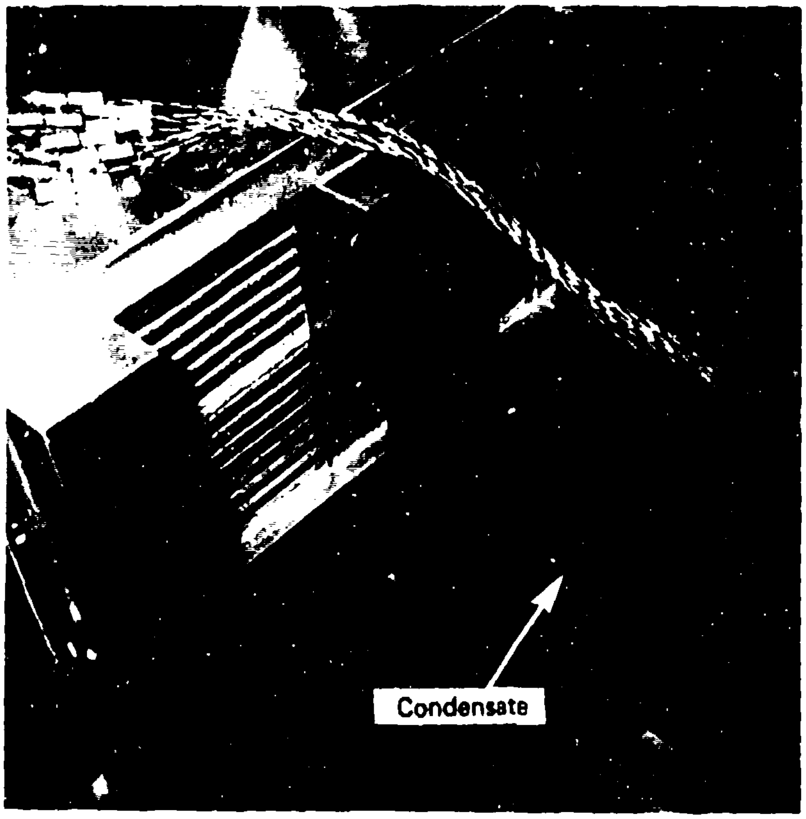


FIG. 9. COOLING UNIT (EVAPORATORS)

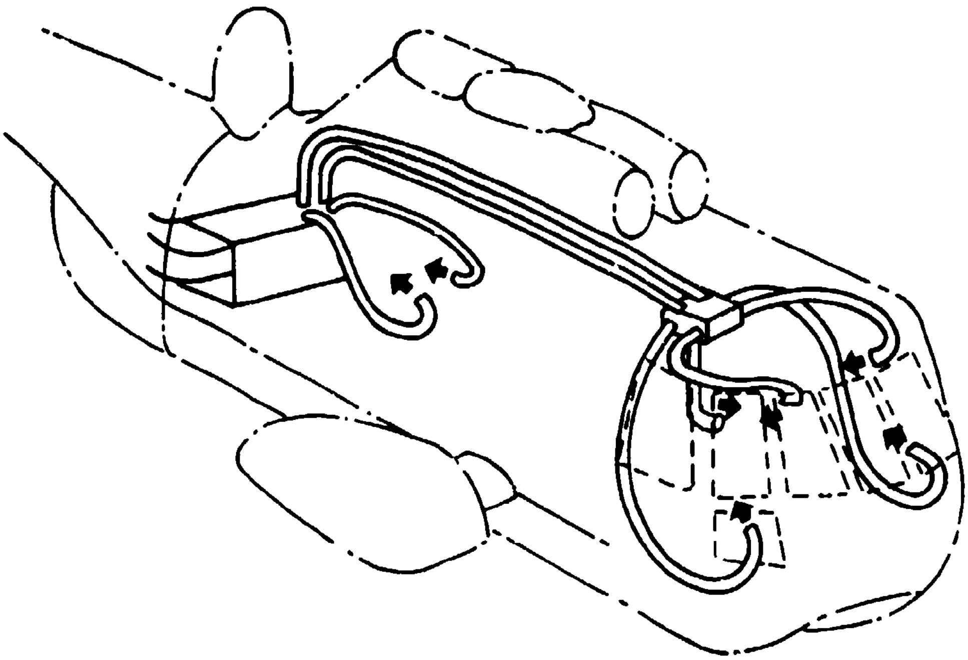


FIG. 10. DUCTING LAYOUT FOR COOLING AIR

FIG. 11. NAVIGATOR COOLING AIR OUTLET

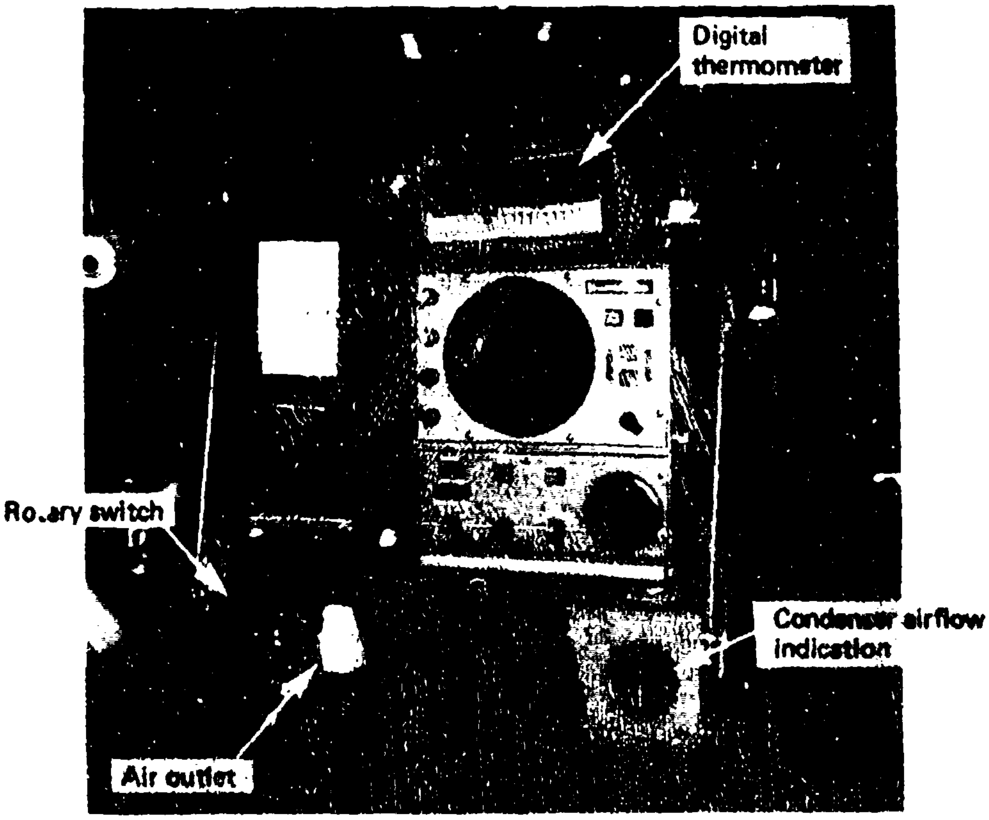


FIG. 12. SONAR OPERATOR COOLING AIR OUTLET

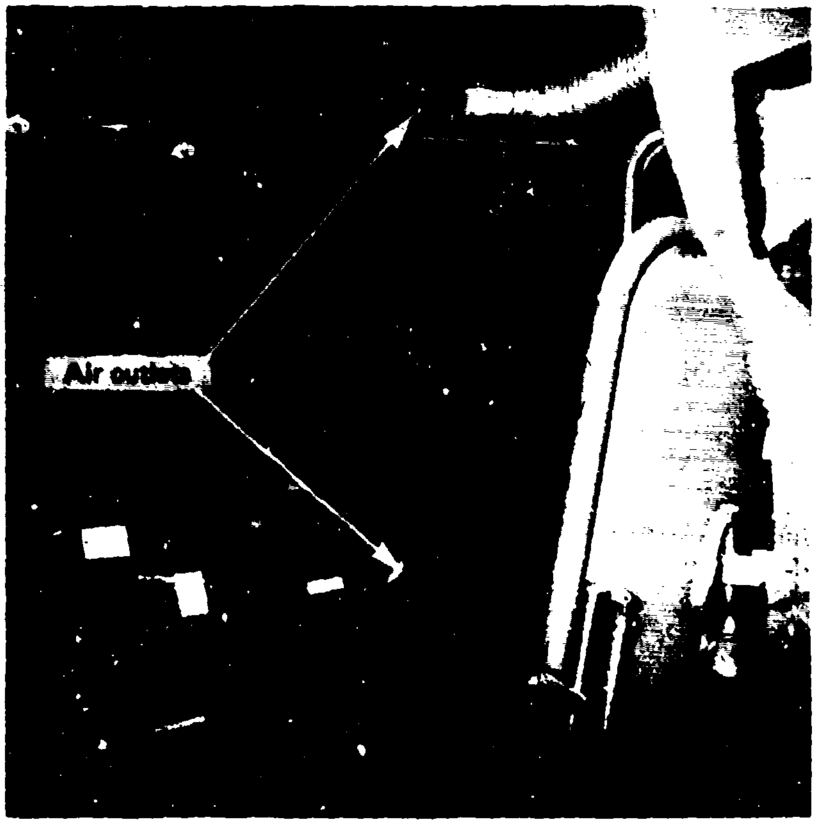


FIG. 13. PILOT COOLING AIR OUTLET

FIG. 14. CO-PILOT COOLING AIR OUTLET

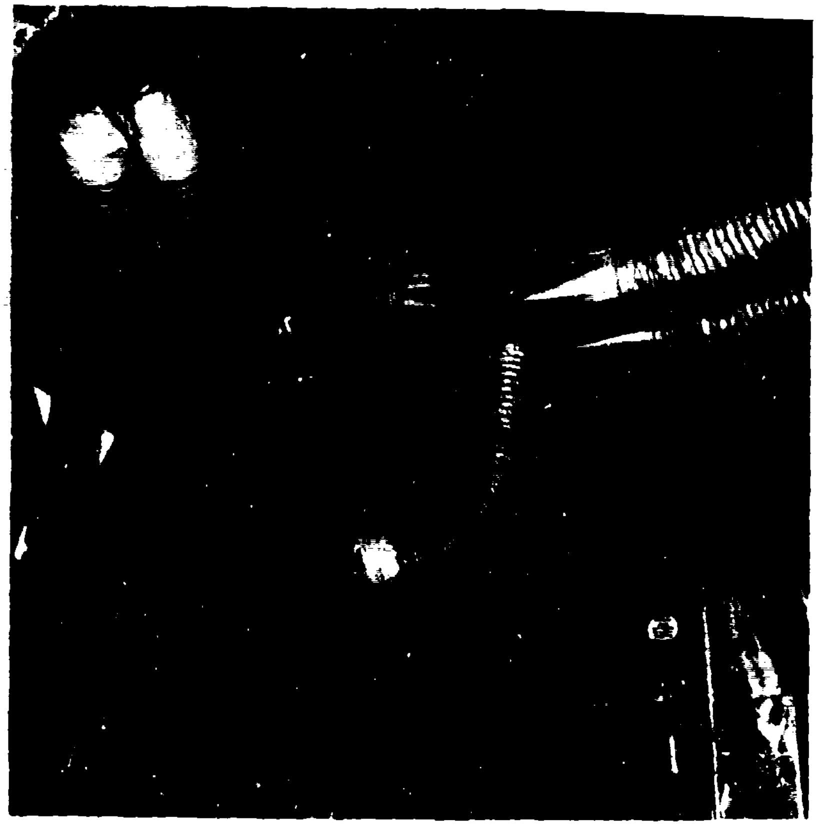


FIG. 15. COOLING AIR DISTRIBUTION BOX (FORWARD CABIN)

FIG. 16. OVERHEAD 150mm DUCTING

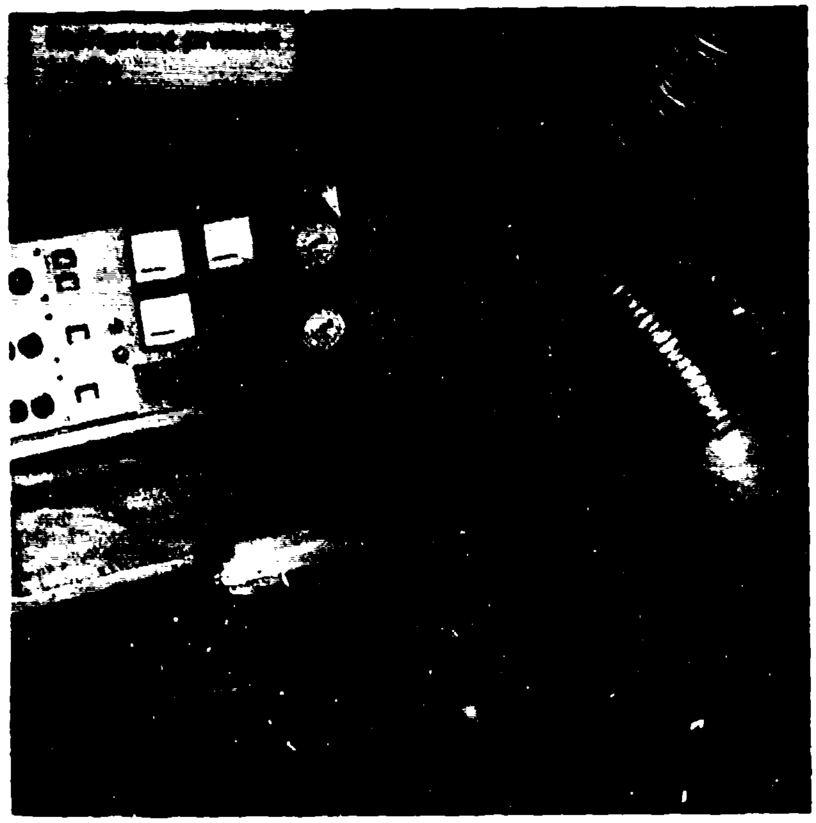


FIG. 17. COOLING AIR OUTLETS FROM AIRCONDITIONING UNIT

FIG. 18. SONAR OPERATOR–NAVIGATOR DRY AND WET BULB TEMPERATURE MEASUREMENT

FIG. 19. TEMPERATURE MEASUREMENT LOCATION BEHIND PILOT'S SEAT

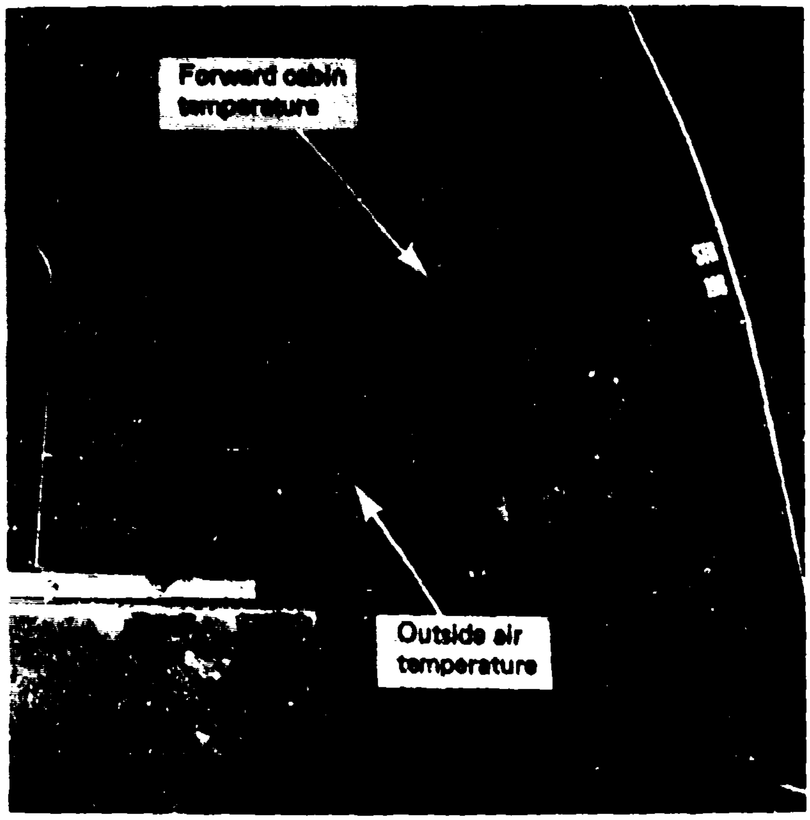


FIG. 20. OUTSIDE AIR AND FORWARD CABIN AIR TEMPERATURE MEASUREMENT LOCATIONS

FIG. 21. COCKPIT BLACK GLOBE

region due to small localised heating by electronic components; these readings are therefore disregarded.

The cabin air humidity was measured between the sonar and radar consoles (Fig. 18). Outside air temperature was measured in the cabin ventilation air inlet duct (Fig. 20). The cockpit black globe temperature was measured by a 150 mm black globe (Fig. 21). These temperature measurement points are summarised in Table 1, as are the wet and dry bulb temperatures of the air passing through the evaporators and condensers (see also Fig. 5). The temperatures were displayed on a Fluke 2100A, ten channel digital thermometer, which, in conjunction with a ten position rotary switch (Fig. 12) enabled the manual recording of temperatures from 18 locations. Additional wet and dry bulb temperature measurements were taken throughout the cabin using a sling psychrometer.

TABLE 1

Temperature Measurement Locations

Thermo-couple no.	Location	Figure no.	Digital Thermometer channel	Rotary switch no.
1	Refrigerant, outlet compressor 2	5	0	1
2	Refrigerant, outlet evaporator 2	5	0	2
3	Refrigerant, outlet evaporator 1	5	0	3
4	Refrigerant, outlet compressor 1	5	0	4
5	Condenser air outlet dry bulb	5	0	5
6	Condenser air inlet wet bulb	5	0	6
7	Condenser air inlet dry bulb	5	0	7
8	Evaporator air in dry bulb	5	0	8
9	Evaporator air in wet bulb	5	0	9
10	Evaporator air out dry bulb	5	0	10
11	Cockpit black globe	21	1	
12	Behind pilot's seat	19	2	
13	Forward cabin compartment	20	3	
14	Forward sonar—navigator console	—	4	
15	Sonar—Navigator dry bulb	18	5	
16	Forward sonar—Navigator console	—	6	
17	Sonar—Navigator wet bulb	18	7	
18	Outside air temperature	20	9	

3.4.2 Refrigerant Temperature and Pressure

Refrigerant temperatures were measured by thermocouples projecting into the refrigerant stream; the locations are indicated in Figure 5 and listed in Table 1. Refrigerant pressures were measured at the suction and discharge sides of the compressors; the gauges are shown in Figure 17.

3.4.3 Electrical—Current and Voltage

Steady-state currents and voltages were indicated on the instruments as shown in Figure 17, which were: ammeter M & W EQ72R 0–40/80 A; voltmeter M & W EQ72R 0–300 V.

Transient currents and voltages on start-up were measured with a portable Tektronix 214 Storage Oscilloscope.

3.4.4 Airflow Measurement

The airflows through the evaporator and condenser were measured by means of static pressure tapping points to record the pressure drop across each matrix. The condenser airflow was continuously monitored by an aircraft airspeed indicator (as this was the most readily available differential pressure gauge)—see Figure 12. Thus any changes in condenser airflow due to rotor downwash and the aircraft velocity could be readily observed.

3.4.5 Condensate

Condensate was collected in the container shown in Figure 9; the condensate was weighed periodically during the tests.

4. FLIGHT TRIALS RESULTS

The ARL cooling unit was flight-tested for eight hours, and ground run for a further eight hours. No operational problems were encountered with the cooling unit and airflow distribution. The cooling capacity of the condenser appeared, however, to be marginal, even at the moderate ambient temperatures (30°C) of the flight trials. The high pressure cut-out, originally set for 1·7 MPa (250 psi) had to be re-set to 2·0 MPa (300 psi). The highest condensing temperatures were encountered in the hover configuration, where exhaust gas was drawn into the condenser cooling air inlet. Had the unit been flown in higher ambient temperatures, of the order of 43°C, then it is quite probable that cooling of the condenser would have been inadequate, in which case several possible immediate modifications would have been to:

(*a*) increase condenser fan speed (some capacity existed for this);
(*b*) increase ram effect on condenser inlet, and limit flight trials to forward flight only; and
(*c*) decrease cooling effect and hence decrease condenser load.

4.1 Daily Summary of Cooling Unit Tests

The cooling unit was tested during ground running and in flight; a summary of the test series from 12 December 1978 to 7 February 1979, is given in Table 2.

4.2 General Performance of the Cooling Unit

4.2.1 Mechanical Performance

No mechanical problems were encountered during the tests; the unit did not require any adjustment or maintenance. No refrigerant leakage was observed; replenishment of oil or refrigerant was not required during the two months that the unit was at Nowra Naval Air Station.

4.2.2 Noise and Vibration

No measurements were taken of noise and vibration generated by the airconditioning unit. However, subjectively, no increase in the overall cabin noise level was detectable when the unit was started in flight. The slight floor vibration observable when the aircraft was stationary was not detectable over the general vibration level while in flight. The flight noise and vibration levels in the Sea King are of course quite high (Pavia and Edwards 1977).

4.2.3 Electrical System Effects

(*a*) Starting surge currents are illustrated in Figures 22 and 23; motor 1 recorded a peak of 72 A rms for 0·5 s, motor 2 a peak of 100 A rms for 0·5 s.
(*b*) Voltage fluctuations: no departure from the no-load voltage of either the 200 V or 28 V aircraft supplies was observed on start-up or on normal operating load.
(*c*) Stabilised normal operating currents: the stabilised maximum operating currents were 18 and 19 A rms for motors 1 and 2 respectively. Hence the total load of the air-conditioning unit was 12·8 kVA.

TABLE 2

Daily Summary of Cooling Unit Tests

Date	Remarks
12 December 1978	The cooling unit was test run in the aircraft, on ground-based power supplies. Ground and flight testing to await aircraft serviceability.
23 January 1979	Aircraft serviceable. Installation complete. Electrical starting load analysed. Initial test flight undertaken, of short duration. No operational problems with cooling equipment.
24 January 1979	A test flight of 1½ hours duration, in an OAT* of 23°C. The subsequent discovery of inward air leakage tends to invalidate results from this flight. The overpressure cut-outs (set to 1·7 MPa (250 psi)) operated; these were later re-set to 2·0 MPa (300 psi).
26 January 1979	Ground run for 15 minutes in an OAT of 21°C, with aircraft engines running. Insufficient time for temperatures to stabilise.
1 February 1979	The source of ambient air infiltration was located prior to this test. The unit was ground-run for two hours in full solar radiation and OAT of 30°C.
2 February 1979	This was the last day available for flight trials during the 1978–79 Australian summer. A flight test of three hours duration was undertaken in outside air temperatures of 25–28°C. The cooling unit was restarted in flight without adverse effect on the aircraft systems. Due to other concurrent (unrelated) tests, the altitude, and hence air temperature, varied during the flight (see Fig. 25).
6 February 1979	Ground run in light cloud cover, OAT 23°C, two hours duration.
7 February 1979	Ground run inside hanger, two hours duration, 25°C OAT. The small cooling load led initially to evaporator icing; this was eliminated by restricting the flow to one half of the evaporator, for this and the following test.
7 February 1979	Ground run outside hangar, in full solar radiation, two hours duration, OAT 26°C.

* Outside air temperature.

4.2.4 Crew Reaction

The crew for the flight trials comprised pilot, co-pilot and observer, the sonar operator seat being occupied by an ARL officer (to record cabin temperatures and humidity, and operating parameters of the airconditioning unit). All of the crew had previously flown in the Sea King in hot climatic conditions. The crew considered the cabin environment to be quite acceptable, and a very great improvement over the cabin environment of an uncooled aircraft in similar climatic conditions. The quite high cooling air outlet velocities did not appear to concern the crew, though they considered that directional control of outlet air would be advisable in a prototype/production version. Initially the lower pilot outlet (Fig. 13) was directing a cold jet of air on the pilot's knee; this was rectified by tilting the outlet. Some concern by the pilot was expressed regarding the capability of the cooling unit to provide an acceptable cabin environment in more severe climatic conditions than encountered on test. As discussed later in this report, a greater cooling capacity than that of the trials unit, is recommended for a prototype/production version.

4.3 Test Data

The test results from the trials are summarised in Appendix 2. The results included are those from 1 February 1979 to 7 February 1979. Earlier results, before ambient air inflows were prevented, are not included. Results from the series of five tests are shown graphically in Figures

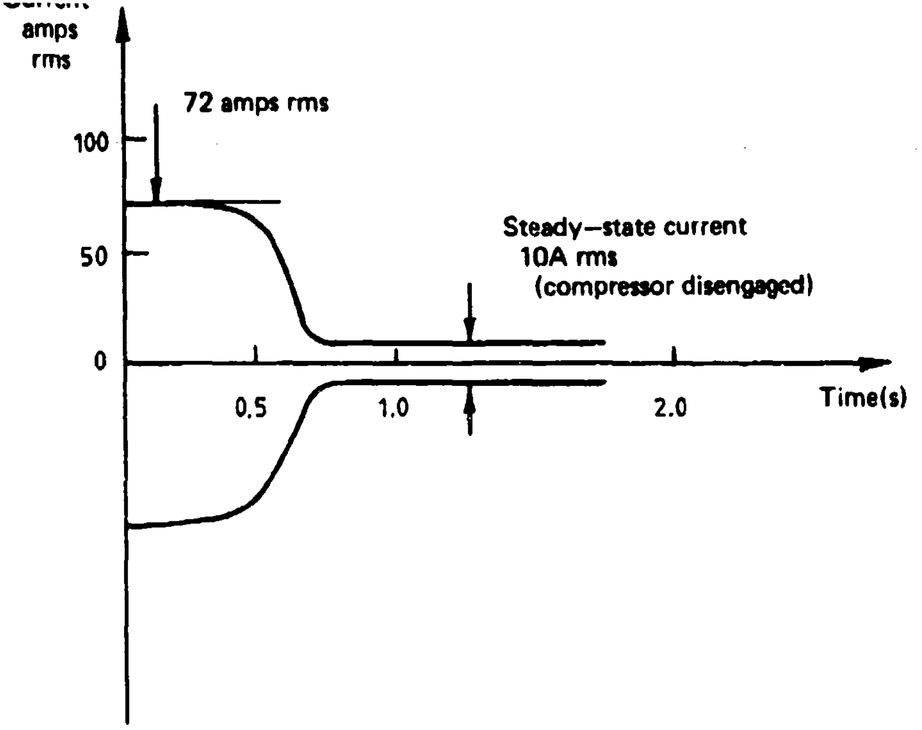


FIG. 22. ENVELOPE OF PEAK—PEAK CURRENT SURGE MEASUREMENT FOR START-UP OF MOTOR 1

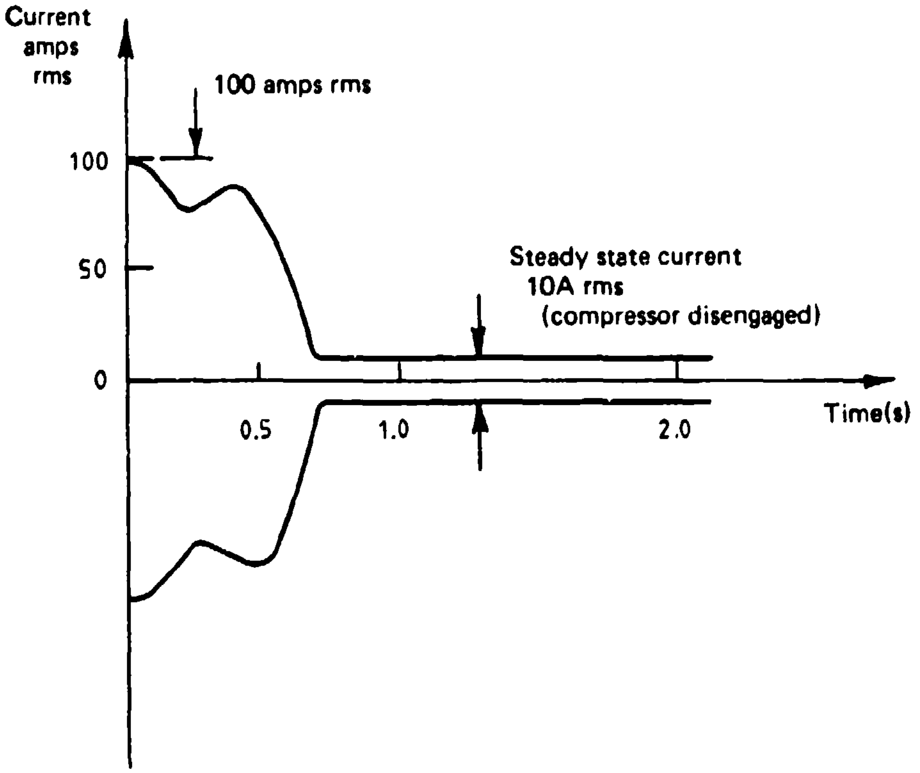


FIG. 23. ENVELOPE OF PEAK—PEAK CURRENT SURGE MEASUREMENT FOR START-UP OF MOTOR 2

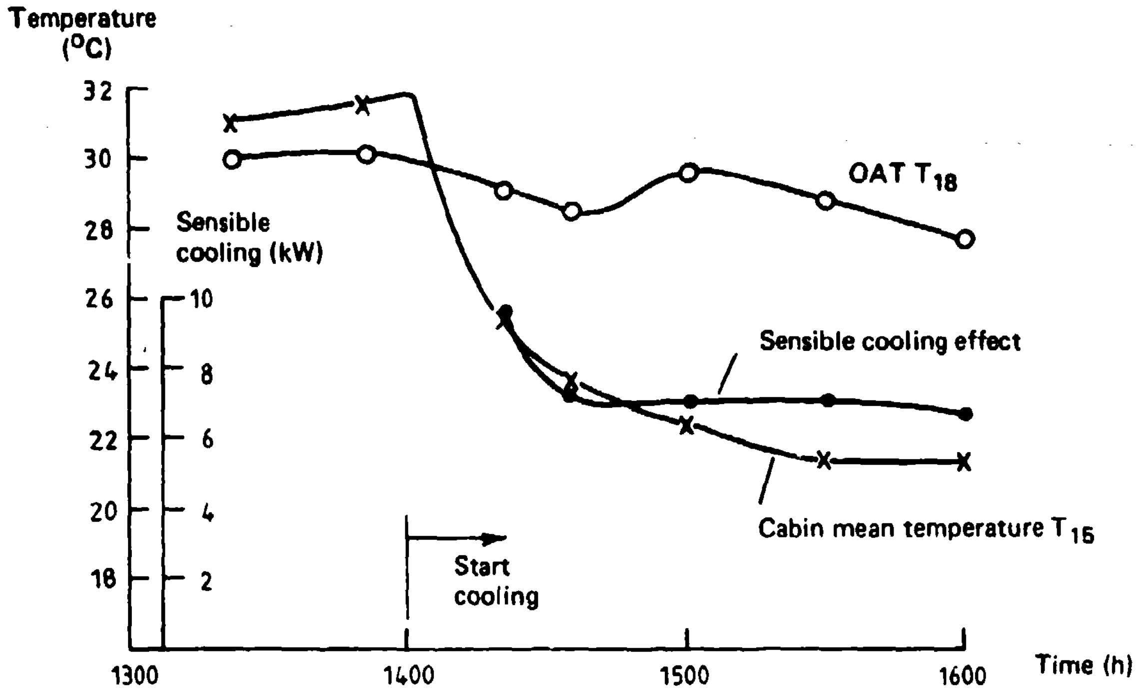


FIG. 24. TEMPERATURES AND COOLING EFFECT FOR GROUND RUN FEBRUARY 1 1979.

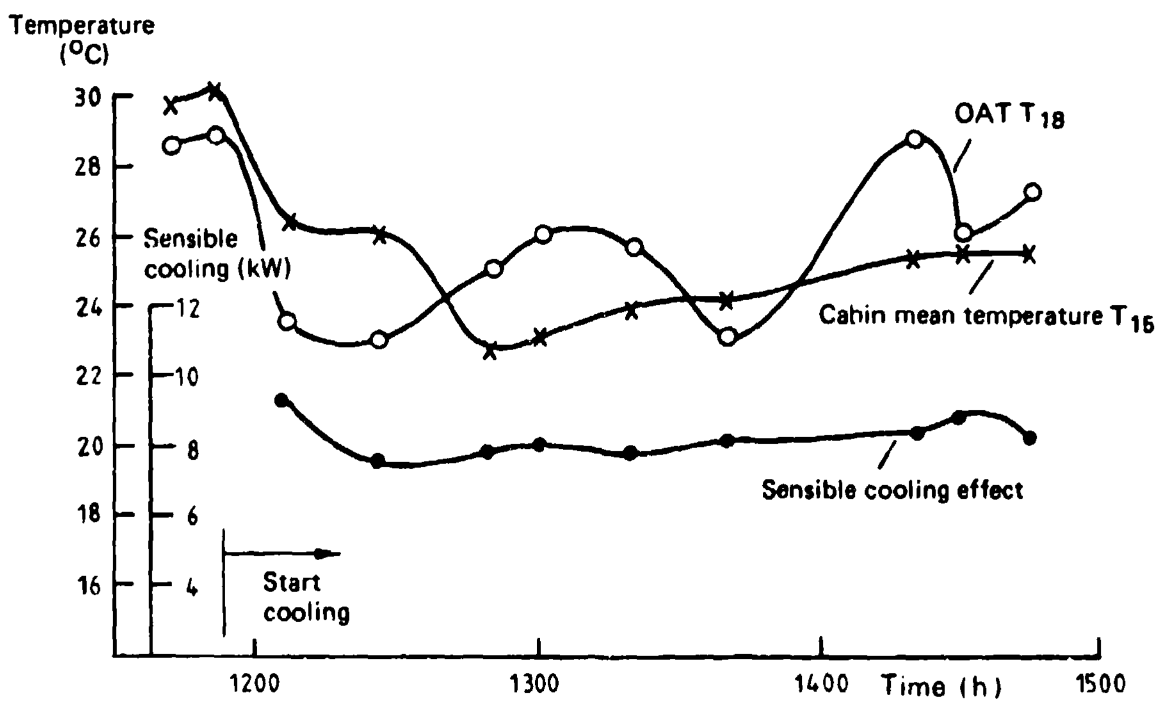


FIG. 25. TEMPERATURES AND COOLING EFFECT FOR FLIGHT TEST FEBRUARY 2 1979.

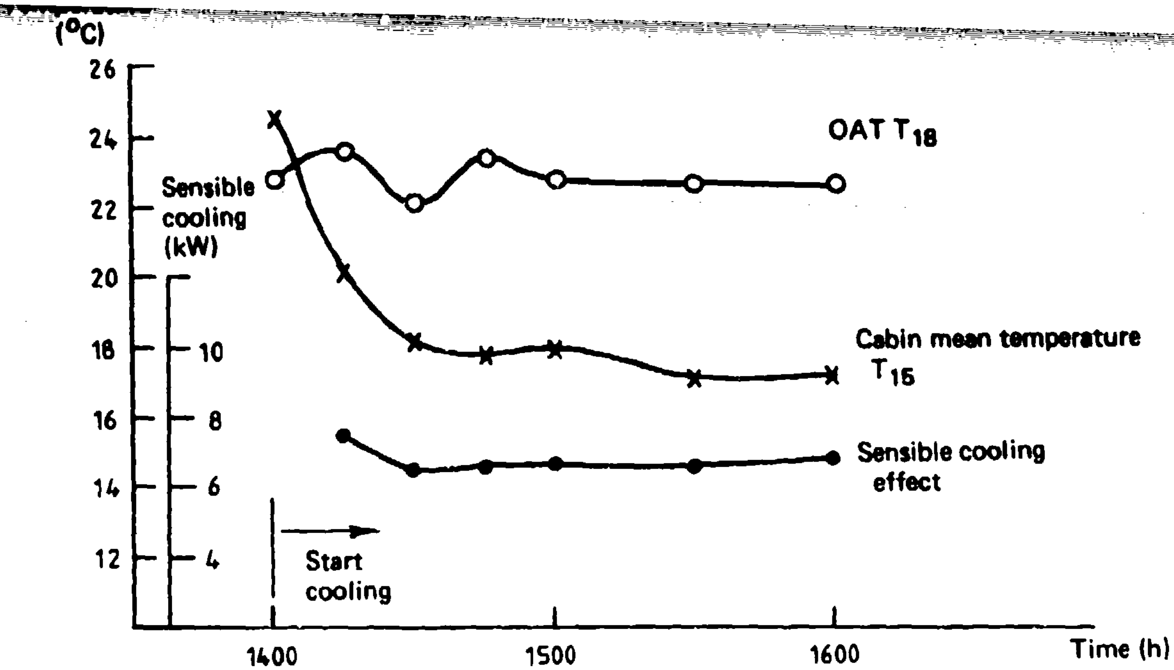


FIG. 26. TEMPERATURES AND COOLING EFFECT FOR GROUND RUN FEBRUARY 6 1979.

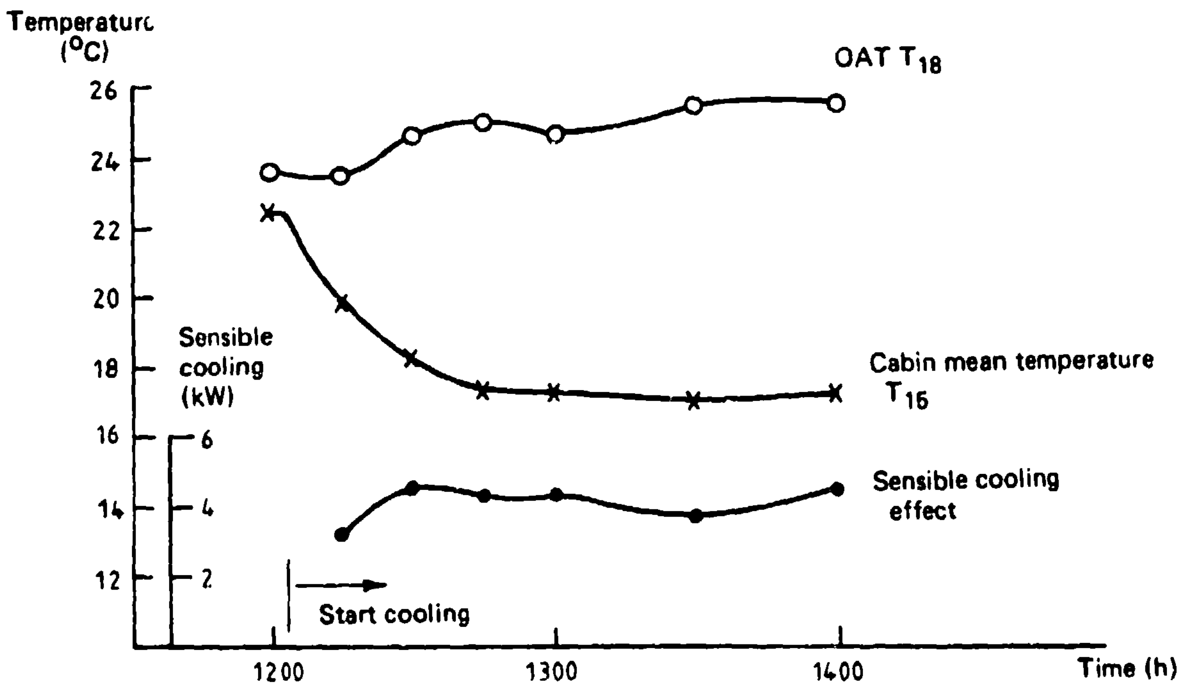


FIG. 27. TEMPERATURES AND COOLING EFFECT FOR TEST IN HANGAF FEBRUARY 7 1979.

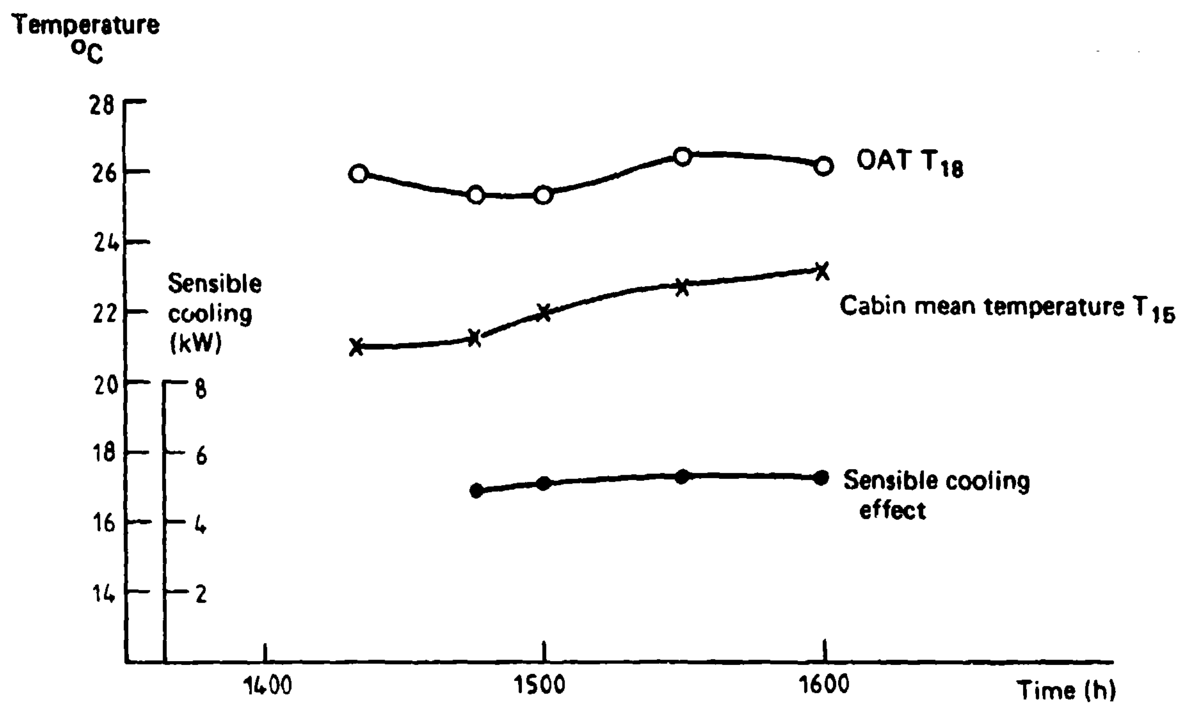


FIG. 28. TEMPERATURES AND COOLING EFFECT FOR GROUND RUN IN SOLAR RADIATION FEBRUARY 7 1979

24–28, where the outside air temperature, cabin mean temperature, and the sensible cooling effect of the ARL cooling unit are plotted against time. The airflows and pressure rises through the cooling unit are summarised in Appendix 3, and the basis of the calculations for cooling effect is given in Appendix 4.

5. ANALYSIS AND DISCUSSION

5.1 The Cabin Heat Balance

The trials results have been used to improve the accuracy and give a more general presentation of the initial heat balance equation (4), and so enable

(*a*) the quantification of the different sources of heat loads, and the insulation values of cockpit and cabin;

(*b*) the extrapolation of the flight test results, which were taken in ambient temperatures not over 30°C, to estimate the cooling required at higher ambient air temperatures, up to 43°C.

There are significant differences between the heat balance for the ground and in-flight cases; the general heat balance equation is described in the following section 5.1.1, and the two particular cases in Section 5.1.2 and 5.1.3.

5.1.1 General Heat Balance Equation

The general heat balance equation for the cabin is

$$Q_m+Q_f+Q_{fa}+Q_e+Q_{en}+Q_w+Q_s = Q_c \qquad (5)$$

where Q_m = metabolic heat output of occupants (kW),

Q_f = fan heating of ventilation air (kW),

Q_{fa} = heat load of ventilation air (kW),

Q_e = electrical equipment heat load (kW),

Q_{en} = heating from engine and exhaust gas (kW),

Q_s = solar radiation transmitted through transparencies (kW),

Q_c = heat removed from cabin by cooling unit (kW),

Q_w = heat conduction through aircraft skin (kW).

Note also that

$$Q_{fa} = C_p m_f (T_a - T_c) \qquad (6)$$

where m_f = ventilation air mass flow (kg/s),

T_a = outside air temperature (°C),

T_c = cabin mean air temperature (°C),

C_p = specific heat of air (kJ/kg °C),

and

$$Q_w = \{A_s(h_r+h_c)(T_a-T_c)+A_t[\epsilon_s Q_{si}+(h_c+h_r)(T_a-T_c)+\delta T_{sky}h_r]\}\{h_w/(h_w+h_r+h_c)\} \qquad (7)$$

where A_s = effective area of fuselage not exposed to solar radiation (m²),

A_t = fuselage skin exposed to solar radiation (m²),

h_w = overall heat transfer coefficient (interior air–exterior skin surface) (kW/m² °C),

h_r = linearised radiation exchange coefficient (kW/m² °C),

h_c = convective heat transfer coefficient (fuselage skin surface–outside air) (kW/m² °C),

ϵ_s = fuselage emissivity at solar radiation wavelengths,

Q_{st} = incident solar radiation (kW/m²),

δT_{sky} = differential between ambient and effective sky temperature $(T_{sky}-T_a)$ (°C),

T_{sky} = effective sky temperature (°C).

The derivation of the cabin heat balance (summarised by the three equations (5)–(7)), and experimental evaluation from flight trials results of the heat transfer coefficient h_w, and heating due to engine exhaust gas Q_{en}, is described in detail by Rebbechi (1979).

5.1.2 Cooling of Aircraft in Flight

Considerable simplification of the general cabin heat balance equation can be made for the in-flight case. Consider now Equation (7); as the aircraft forward speed increases $h_c \gg h_w, h_r$.

Equation (7) can then be brought to the form

$$Q_w \simeq Ah_w(T_a-T_c) \tag{8}$$

where $A = (A_t+A_s)$ = total effective area, for heat transfer, of fuselage (m²).

The effect of the high external convective heat transfer coefficient h_c is then to bring the outer skin surface temperature to outside air temperature; radiation exchange with surroundings or incident solar radiation will not affect the skin surface temperature, and hence heat transfer into cabin. The benefit of painting the upper aircraft surface white will thus be seen in reduced heat input to the cabin for the parked aircraft, but will not affect the heat transfer for the in-flight case.

Substituting Equations (6) and (8) into Equation (5) gives

$$Q_m+Q_f+(T_a-T_c)(Ah_w+C_pm_f)+Q_e+Q_{en}+Q_s = Q_c, \tag{9}$$

and from Rebbechi (1979) the magnitudes of the terms in Equation (9) have been estimated as follows in Table 3.

TABLE 3

Magnitude and Definition of Terms in Equation [9]

	Parameter	Magnitude
Q_m	Metabolic heat output of occupants	0·48 kW (4 persons)
Q_e	Electrical equipment heat load	0·5 to 3·11 kW
Q_{en}	Heating from engine and exhaust gas	2·39 kW
Q_s	Solar radiation transmitted through transparencies	2·49 kW
m_f	Ventilation air mass flow	0·045 kg/s
h_w	Outer skin to interior air heat transfer coefficient	0·0124 kW/m² °C
A	Fuselage area	40 m²
Q_f	Fan heating of ventilation air (applies only to inefficient ventilation arrangement in trials aircraft)	0·32 kW
T_a	Outside air temperature	
T_c	Cabin mean air temperature	
Q_c	Heat removed from cabin by cooling unit	

The heat balance equation, (9), can then be written as

$$5{\cdot}36+Q_e+0{\cdot}54(T_a-T_c) = Q_c, \tag{10}$$

where the aircraft is exposed to full solar radiation, has four occupants and $Q_f = 0$. This equation, which is for sensible heat loads only (as distinct from later equations which include latent heat of condensation of moisture in the air), is illustrated graphically in Figure 29, for the likely range of electrical cooling load requirements.

5.1.3 Cooling of Parked Aircraft

The discussion here describes the heat balance of a cooled parked aircraft, with doors and windows closed. The general heat balance equation (5) includes the uncooled aircraft case (where $Q_c = 0$); however, when the aircraft is parked in full solar radiation it is unlikely that all doors and windows will be closed, in which case Equation (5) would not apply.

In Figure 30 a graphical interpretation is given of the cabin cooling requirements *vs.* wind velocity, for a range of cabin temperature differentials from outside ambient. This figure is derived from Equation (5); details of the constants are given in Appendix 5. It applies to a parked aircraft exposed to full solar radiation, clear sky, no occupants, all doors and windows closed, and ventilation airflow of 0·045 kg/s.

From Figure 30, the effect of wind velocity changes as the temperature differential increases; where $(T_a - T_c) = 0$, the effect of rising wind velocity is to cool the skin surface exposed to solar radiation (the remainder of the fuselage surface being at ambient temperature). Where $(T_a - T_c)$ is greater than zero, an increase in wind velocity will raise the surface temperature (which is less than ambient for that portion of the fuselage area—77%—not exposed to solar radiation, and so tend to increase the cooling requirement).

An analysis of the transient cooling case is not included here; the test results (see Figs. 24–28) do however contain sufficient data for an analysis. Further discussion on the relevance of transient cooling estimates is contained in Section 5.2.6.

5.2 Vapour Cycle Cooling System Requirements

5.2.1 Definition of Cabin Environment

A vapour cycle system tends to give a dry cabin environment (as evaporator outlet air temperatures will typically be less than 12°C), so that the maximum WBGT criterion of 28°C established in Section 2.2 could be achieved with quite high air temperature of 37°C in the region of the crew, with accompanying black globe temperature of 43°C. These high temperatures will result in crew dehydration, which is especially important in the context of Sea King missions which may last at least four hours; other adverse physiological effects may also result (White 1978). For these reasons the crew areas will be designed for a dry bulb temperature of 33°C, which will result in a crew WBGT of 26°C, where $T_g = T_c + 6$, and cabin moisture content 0·010 kg moisture/kg dry air. This cabin moisture content is conditional on the evaporator maintaining a particular outlet air temperature, in this case saturated air at 12°C. Due to the small degree of spot cooling effect evidenced during the flight trials, it is estimated that the cabin bulk air temperature T_c, which is used to estimate cabin heat loading, can be 3°C higher than that of the crew regions, resulting in a design cabin air temperature $T_c = 36$°C.

5.2.2 Ventilation and Air Distribution Requirements

The recirculating airflow during the tests of the ARL cooling unit was 0·68 kg/s. This is a greater airflow than required for satisfactory distribution of air to four occupants; for example the vapour cycle cooling system of the Presidential VH-3A helicopter utilised an airflow of 0·46 kg/s. The degree of spot cooling obtained is affected to only a small degree by the outlet velocity; the size and shape of the outlet duct is the principal determining factor (Robeson and Downie 1978; American Society of Heating, Refrigeration and Airconditioning Engineers 1966).

Within the constraints of possible duct sizes, and volume of air available, it is not realistic to expect a very great degree of spot cooling; rather the emphasis should be on maintaining a reasonable airflow velocity around the crew to aid in heat transfer (3 m/s for areas other than face and exposed areas (Hughes 1968)), and to avoid impinging cool airflows onto the fuselage walls and transparencies.

There is a lower limit to the recirculating airflow required, if freezing in the evaporator is to be avoided. At an airflow of 0·4 kg/s and a sensible cooling of 10 kW, a temperature fall of 25°C will occur in air pasing through the evaporator.

The pilot and co-pilot are exposed to direct solar radiation through the transparencies; for this reason, and also the greater heat transfer through the transparencies, it is desirable that more cooling air be directed to the pilot crew area than to the sonar operator–navigator area. During flight trials 66% of air was directed to the front pilot area, and 34% to the rear; this ratio was considered by crew members to be quite acceptable.

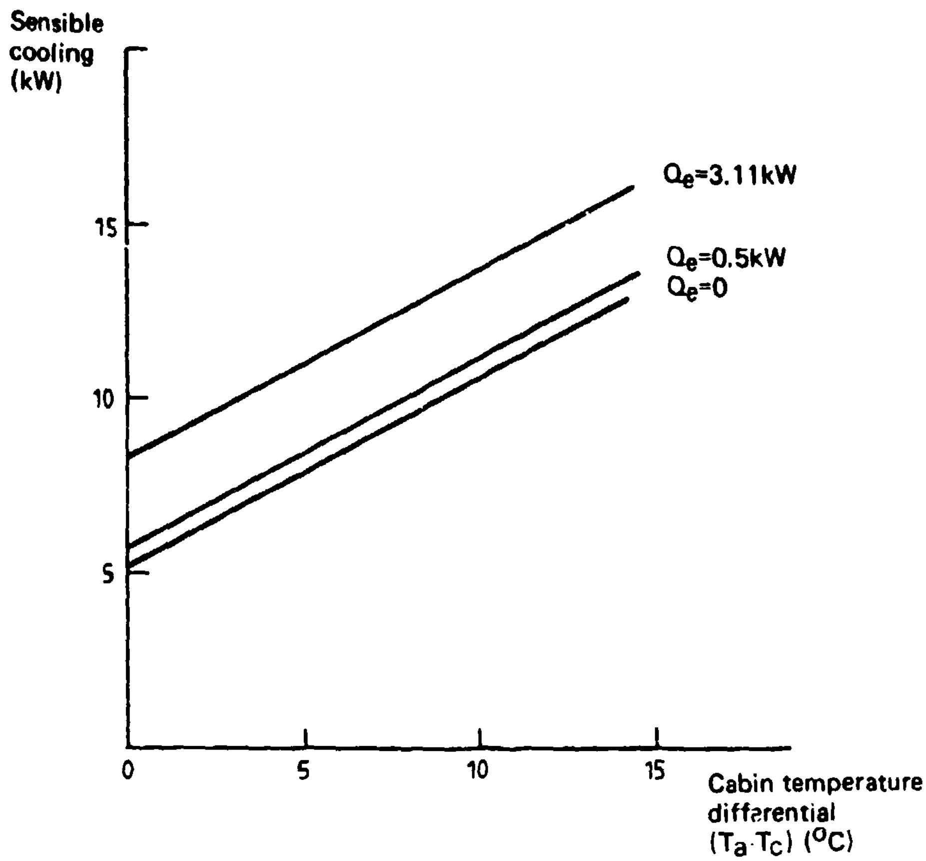


FIG. 29. SENSIBLE COOLING REQUIREMENT VS. CABIN TEMPERATURE DIFFERENTIAL

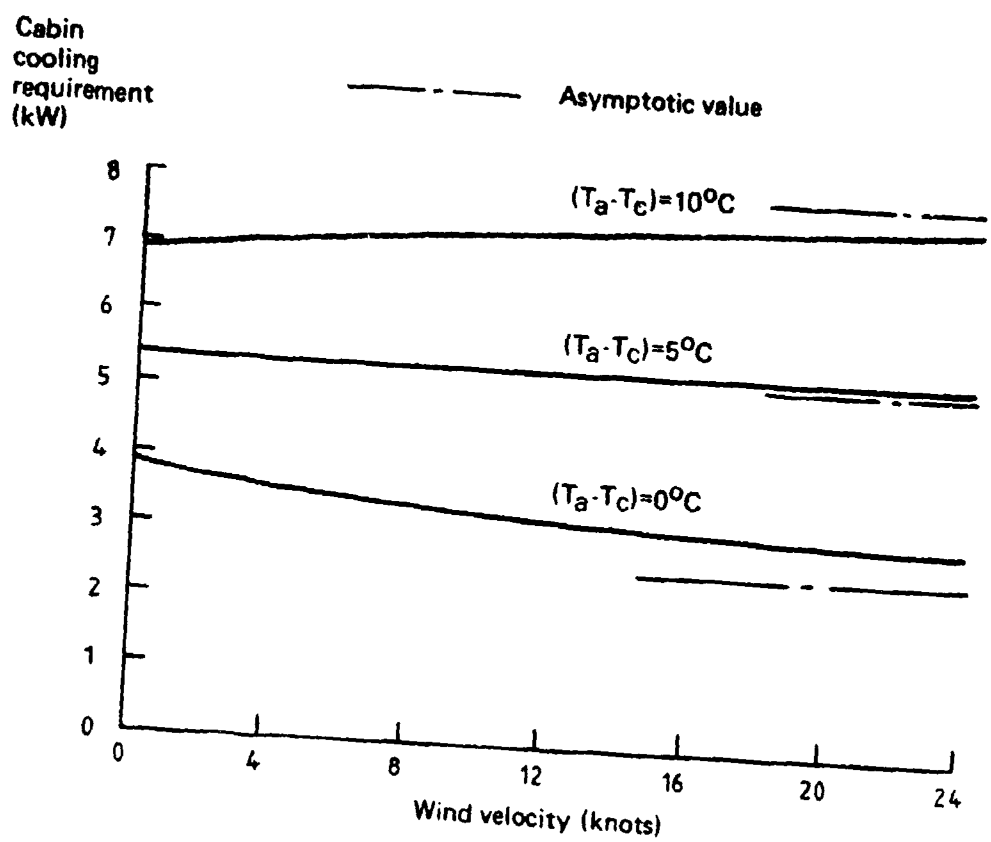


FIG. 30. GROUND COOLING REQUIREMENTS – DOORS CLOSED, ENGINES NOT OPERATING

The ventilation air requirements for passenger carrying aircraft is recommended by airline operators to be 0·009 kg/s (1·2 lb/min) per passenger during flight (Timby 1969). However, Timby concludes that from a purely physiological aspect fresh air supplies could be reduced to 0·002 kg/s (0·25 lb/min). As the Sea King normally carries a crew of four, the ventilation air requirements will be 0·036 kg/s if the nominal recommendation of 0·009 kg/s per crew member is followed. There will then exist a reserve capacity for up to 20 persons if the physiological aspect only is considered. During the flight trials, however, the ventilation airflow was 0·045 kg/s, as it was envisaged that the crew for these trials would generally be greater than four. This airflow was then used as a basis for the calculation of total cooling requirements in a prototype/production unit. A small decrease (approximately 0·3 kW) in cooling requirements will be made if the lower flow of 0·036 kg/s is used.

5.2.3 Cooling Capacity Requirement for In-flight Cooling System

From Section 5.1.2 the heat balance equation for an in-flight aircraft, exposed to full solar radiation, with four occupants, and a ventilation airflow of 0·045 kg/s, is

$$5 \cdot 36 + Q_e + 0 \cdot 54(T_a - T_c) = Q_c. \tag{11}$$

Equation (11) is for sensible heat flows; for total cooling requirements we need to include the latent heat of condensation of moisture from air passing through the cooling unit evaporator, which arises from:

(*a*) the initial reduction in moisture content of cabin air;

(*b*) the water loss from occupants; and

(*c*) the reduction in moisture content of cabin ventilation air (drawn in from outside of cabin).

The steady-state latent heat of condensation is calculated for the conditions given in Table 4; the water loss from occupants is neglected as it is small (about a quarter of the metabolic heat rate in comfort conditions (Kerslake 1972)). The latent heat of condensation, Q_l, is given by

$$Q_l = m_f h_{fg} \delta_r, \tag{12}$$

where m_f = ventilation air mass flow kg/s,

h_{fg} = heat of vaporization, 2454 kJ/kg,

δ_r = decrease in humidity ratio.

TABLE 4

Outside air humidity ratio	Outside air temperature (°C)	Ventilation mass flow (kg/s)	Evaporator air temperature (°C)	Latent heat of condensation (kW)
0·027	30–38	0·045	12	2·00
0·021	43	0·045	12	1·35

The two possible alternatives in Table 4 for the most severe cooling case are derived from Figure 1; that is, an outside air temperature of 38°C and humidity ratio 0·027, or an outside air temperature of 43°C and humidity ratio 0·021. Using then the design cabin bulk air temperature of 36°C (Section 5.2.1), the total cooling requirement for the former case is $(8 \cdot 44 + Q_e)$ kW, and for the latter case $(10 \cdot 49 + Q_e)$ kW. The magnitude of the electrical equipment heat load Q_e is discussed in the following section.

5.2.4 Minimisation of Cabin Heating by Avionics

The electrical energy dissipated in the form of heat in the cabin is estimated to be as follows:

Cockpit and cabin instrumentation	0·50 kW
Radar	0·38 kW
Sonar	2·23 kW
Total:	3·11 kW

These estimates were obtained from aircraft electrical load sheets held at Nowra Naval Air Station.

Several alternatives to minimise the heat loading are to:

(*a*) duct equipment cooling air overboard;

(*b*) use external ambient air for cooling of equipment—i.e. provide ducting to take in ambient air, pass it through the equipment and exit it overboard.

With alternative (*a*) above the equipment is in effect being used as an outlet for the cabin ventilation; the entry temperature of air to the equipment is then the mean cabin temperature. This method of cooling is limited by the quantity of ventilation air, and also by the presence of air leakage around doors and windows. It is impracticable to eliminate all of this leakage; thus, to avoid the ingestion of exhaust gas (by drawing air in from the rear part of the aircraft) the equipment cooling air is restricted to less than the ventilation airflow. If the ventilation airflow is increased to supply additional equipment cooling air, then this represents an additional heat load on the cabin. For example, if the cabin temperature is δT_d degrees below ambient, and the allowable temperature rise through the equipment is δT_e, then the ratio of the sensible heat load due to ventilation air (Q_{ta}) divided by the equipment cooling effect (Q_{ec}), is

$$Q_{ta}/Q_{ec} = \delta T_d/\delta T_e. \tag{12}$$

Then, if for example $\delta T_d = \delta T_e$, the heat load of the ventilating air equals the electronic equipment heat ejected overboard.

Alternative (*b*) will result in the air entering the equipment at outside air temperature. From the viewpoint of equipment cooling this is an improvement on the present situation, where the equipment is cooled by cabin air, typically 6–10°C above ambient.

There is evidence (German 1974) that electronic component reliability decreases above 15°C, so that there may be advantages in cooling the equipment to a temperature below its "rated" maximum.

Before any decision could be taken on the relative merits of the foregoing alternatives, it is necessary to establish

(*a*) the cooling airflows and allowable temperature rise in each item,

(*b*) whether an improvement in reliability will result from the use of cooler cabin air.

5.2.5 Salt Water Ingestion by Condenser

During operations near to sea level (which are frequently carried out in the anti-submarine role), salt water spray may envelop the aircraft. The small passages of the condenser which typically may run at surface temperatures up to 90°C, would then be particularly susceptible to salt deposition, with resulting overheating and also the possibility of corrosion if unsuitable materials were used. Bench testing of proposed equipment, with salt water introduced into the condenser cooling air stream, will be necessary to assess the severity of this problem, and to establish maintenance procedures.

Details of salt-in-air tests for gas turbines are given in the United States Military Standard MIL-E-17341C (SHIPS). Sea salt concentrations of 0·035 ppm are estimated for an SH3A helicopter hovering 12 m above sea level in light winds (Ashbrooke 1969). In heavy seas the concentration could be much higher; likely maxima will need to be established before carrying out realistic ground tests.

5.2.6 Cooling of Parked Aircraft

The steady-state heat balance equation for the parked aircraft is given in Appendix 5 (Equation (A4)); to bring the cabin to a WBGT of 26°C in an outside air temperature of 43°C, humidity ratio 0·021 and a 10-knot wind, would require a cooling effect of 7·47 kW. This cooling requirement is much less than the in-flight case ($10{\cdot}49 + Q_e$) kW, hence a system which satisfies in-flight requirements will have reserve capacity in the ground case.

The transient cooling case has not been studied in detail, though from the trials results (Figs. 24–28) an equation describing this could have been formulated. However, the transient case is not considered by the author to be particularly relevant; considerable reserve already exists in cooling, for the parked case, in a system which is adequate for flight. Also, an electrically powered vapour cycle cooling unit can be operated from ground power supplies, which are available prior to engine start-up. The duration of ground running time prior to flight, required to bring the cockpit to an acceptable environment, could readily be determined in normal squadron use.

Several points relevant to the initial cooling of the cabin are—

(*a*) The initial cooling effect in humid environments will largely be removal of moisture from the cabin air; the benefit of this will be felt almost immediately by the crew, even though the cabin temperature may still be quite high.

(*b*) From the author's experience it is not essential that the cockpit environment be brought to less than 28°C WBGT *before* crew enter the aircraft; it is, however, important that the cockpit environment is less severe than outside ambient (from which the crew are moving), that it is steadily improving, and that relatively cool air is issuing from cooling air outlets.

5.2.7 Ambient Leakage Air Inflows

It is particularly important with a vapour cycle cooling system that outside air leakage into the cabin be reduced to a minimum. The effect of outside air leakage on the cooling requirement arises in part because of the effect on sensible cooling requirements, which is equal to $C_p(T_a - T_c)m_l$, and the effect on the condensate latent heat cooling load (Section 5.2.3, Equation (12)), which equals $2454\, m_l \delta_r$. In extreme climatic conditions, the condensate cooling load may be (at least) three times the sensible cooling load of the leakage air. The leakage may increase with aircraft age (due to poorly fitting sliding windows, doors, etc.); for this reason some reserve capacity may be necessary in the cooling system to allow for this rather unpredictable cooling load.

5.2.8 Summary of Vapour Cycle System Requirements

The vapour cycle cooling system requirements have been discussed in some detail in the foregoing Sections 5.2.1–5.2.7. There is, however, at the time of writing this report, uncertainty regarding the required cooling capacity; this depends in part upon the avionic electrical heating load on the cabin, which ranges from 0–3·11 kW. Various ways of minimising the cabin heating from this source are discussed in Section 5.2.4, thus the required cabin cooling will depend upon the effectivess of this minimisation. The cabin cooling requirements Q_c (kW), for the climatic extremes referred to in Section 2.1, are given in Section 5.2.3, as

$$Q_c = 10{\cdot}49 + Q_e. \tag{13}$$

Q_e can be expected to have a minimum value, with the aircraft in flight of 0·5 kW (sonar and radar not operating). Depending on the effectiveness of measures to minimise cabin heating by the sonar and radar avionics, the total cabin cooling requirements will range from $Q_c = 11{\cdot}0$ kW (without sonar and radar), to $Q_c = 13{\cdot}6$ kW (including sonar and radar).

These cooling requirements are based on aircraft operation in climatic extremes (see Section 2.1), that is OAT 43°C, and 37% relative humidity, and a cooling unit discharge air temperature of 12°C.

5.3 Air Cycle Cooling Systems

An air cycle cooling system is one in which, in its simplest form, high pressure bleed air is tapped from the engine compressor, cooled through a heat exchanger, then further cooled by expansion through a small high-speed turbine. This system has two distinct advantages over a vapour cycle system; these are small size and low weight. The coefficient of performance is, however, very low, to the extent that sufficient engine bleed air to provide adequate cabin cooling may not be available without an excessive loss of engine performance. In addition to small size and bulk, several other advantages are at times claimed for air cycle systems; these include reliability, simplicity and the use of air as a working medium. These claims need to be regarded carefully, as they are at times made on the basis of comparison with earlier vapour cycle systems, and not those currently in use.

5.3.1 Cabin Heat Balance with an Air Cycle System

The cabin cooling effect, Q_r, of an air cycle system is

$$Q_r = m_{fa}(T_{out} - T_{in})C_p \tag{14}$$

where m_{fa} = cooling air mass flow (kg/s),

T_{out} = cabin outlet air temperature (°C),

T_{in} = cabin inlet air temperature (°C),

C_p = specific heat of air (1·01 kJ/kg °C).

Where the cabin volume is large compared with the cooling airflow, the mean cabin temperature (T_c) will approximate to the outlet air temperature. Hence, the heat load on the cabin, for four occupants and full solar radiation, is, from Equation (10), noting that $m_f = 0$,

$$Q_c = 0{\cdot}50(T_a - T_c)C_p + 5{\cdot}36 + Q_e. \tag{15}$$

Then, from Equation (14), noting that T_{out} is equivalent to T_c, $C_p \simeq 1{\cdot}00$, $T_a = 43$°C (design environment),

$$T_c = (26{\cdot}86 + Q_e + m_{fa}T_{in})/(m_{fa} + 0{\cdot}5). \tag{16}$$

The cooling air requirements for a particular cooling system can now be assessed; if the cabin environment is to be kept to 26°C WBGT, and the cooling air inlet is 4°C (assumed saturated at this temperature) then the mass flow required, where

$$m_f = (26{\cdot}86 + Q_e - 0{\cdot}5T_c)/(T_c - T_{in}), \tag{17}$$

is 0·25 kg/s (33 lb/min), for $Q_e = 0{\cdot}5$ kW.

5.3.2 Comparison Between Air Cycle and Vapour Cycle Systems

At the time of initial investigations by ARL of Sea King cabin cooling (Rebbechi 1977) the only air-cycle proposal being considered was the Normalair-Garrett Commando cooling unit. The performance of this unit was thought at the time to be only marginal; the revised cabin heat loadings as a result of these flight trials have shown that this system would have been quite unacceptable. Calculations in the previous section, 5.3.1, show that a mass flow of 0·25 kg/s would be required; the proposed mass flow of this system was to have been only one-half of this. Normalair-Garrett have, however, since developed a much more efficient air cycle cooling system, initially for the Westland Helicopters "Lynx". The coefficient of performance (COP) for this system, whilst much improved over the Commando system, is still very low (in the region of 0·24 when used in the Sea King). In comparison, with a vapour cycle system an overall COP of at least 1·5 can be expected. When comparing the overall weight of different systems, the power and fuel consumption penalties of the cooling systems should also be considered. For example, an air-cycle system with a bleed air requirement of 0·11 kg/s, will decrease the Sea King engine shaft power by 74 kW at maximum engine power settings; the fuel consumption then being increased by approximately 20 kg/hr. This increase in fuel consumption will be less, however, at cruise power settings.

A vapour cycle system, having a considerably greater cooling capacity, but using only 10 kW shaft power, would increase fuel consumption by only 5 kg/hr.*

5.4 Cabin Environment Control in Cold Ambient Conditions

There has to date been no operational requirement for cabin heating of the RAN Sea King in cold conditions, and heating is not provided at present, although included in Royal Navy Sea Kings. However, as there may at some future time be an RAN requirement, this problem is considered here.

5.4.1 Analysis of Heat Balance in Cold Conditions

From the heat balance equation (9), noting that now

$Q_s = 0 \cdot 0$,

$Q_c = -Q_h$, where Q_h = heating system input,

$Q_e = 0 \cdot 5$ kW,

$Q_m = 0 \cdot 4$ kW (4 persons),

then

$$Q_h = 0 \cdot 54(T_c - T_a) - 3 \cdot 37, \tag{18}$$

where T_a = ambient air temperature (°C),

T_c = cabin air temperature (°C),

Q_h = cabin heating (kW).

Equation (18) is for a ventilation airflow of 0·045 kg/s (6 lb/min). In the absence of heating ($Q_h = 0$), Equation (18) indicates that the cabin temperature will be 6·2°C above outside ambient air temperature.

5.4.2 Heating System Alternatives

Two possible alternatives for heating are to

(*a*) use the vapour cycle cooling system in a reverse cycle (heat pump) mode;

(*b*) use direct electrical heating of the air by resistance wires in the cooling system duct.

Alternative (*a*) is unlikely to be suitable because of icing problems in the outside heat exchanger (which must necessarily be at a temperature lower than the surrounding air), particularly in the icing conditions which a helicopter can be expected to encounter. In view of the considerable reserve of electrical power (approximately 12 kVA), alternative (*b*) represents a satisfactory solution.

6. CONCLUSIONS

The flight tests of the ARL vapour cycle cooling unit have given a practical demonstration of the feasibility of this form of cooling in RAN Sea King helicopters. The tests have enabled refinement of the earlier mathematical model for heat flows in the Sea King helicopter cabin, so that the cooling system capacity required to provide an acceptable cabin environment, from the viewpoint of crew efficiency in climatic extremes, can be assessed.

The required cooling effect of the vapour cycle cooling system has been calculated as ranging from 11·0 kW (without sonar and radar), to 13·7 kW (with sonar and radar electrical heating dissipated in the cabin). Various methods have been described to reduce the cabin heating from avionics; the practical effectiveness of these methods will determine the final cooling system requirements.

* This fuel consumption figure is based on an assumed engine specific fuel consumption of 0·135 mg/J. Where air bleed is used as for the air-cycle system, the fuel consumption increase cannot be calculated directly from the decrease in engine shaft power.

No interference with the electrical or flight systems was observed while operating the trials cooling unit, despite the quite large starting current of 100 A for 0·5 s.

The air distribution system used in flight trials achieved a favourable crew reaction; however, this approval should be seen in the context of the system being a trials unit. A considerably improved layout, having crew control over direction, amount and temperature of air, will be necessary. To arrive at a suitable layout for the prototype, use of a full-size model, which could be readily varied to study air distribution, would be most useful.

From the flight trials results an accurate assessment of the performance of air cycle cooling systems can be made. An early proposal for an air cycle system of 4°C entry temperature and 0·11 kg/s (15 lb/min) mass flow was evaluated, and found to be quite inadequate. Later air cycle systems, as used in the Westland "Lynx" helicopter, provide improved cooling performance; the coefficient of performance of this later system is still, however, very much less (one sixth) than that of a vapour cycle cooling unit. This lower COP would be reflected in higher engine power loss and fuel consumption.

REFERENCES

American Society of Heating, Refrigeration and Airconditioning Engineers (1966). *Ashrae Guide and Data Book, Fundamentals and Equipment for 1965 and 1966*. New York: American Society of Heating, Refrigerating and Airconditioning Engineers, Inc.

Ashbrook, R. L. (1969). *A Survey of Salt Deposits in Compressors of Flight Gas Turbine Engines*. NASA TN D-4999, Lewis Research Centre, Cleveland, Ohio.

Conklin, E. J. (1964). *Model VH-3A Mark VI Airconditioning System Performance Evaluation*. Report Ser 61975, Jan. 1964. United States: Sikorsky Aircraft.

German, G. (1974). Cooling of Electronic Equipment in Relation to Component Temperature Limitations and Reliability. Symposium on Cooling of High Performance Aircraft, at Royal Aircraft Establishment, February 1974.

Hughes, T. L. (1968). *Cabin Air Requirements for Crew Comfort in Military Aircraft*. Tech. Rep. 68304, December 1968. Farnborough: Royal Aircraft Establishment.

Kerslake, D. McK. (1972). *The Stress of Hot Environments*. Physiological Society Monograph. Cambridge University Press.

Ministry of Aviation (1960). Av.P.970. *Design Requirements for Aircraft for the Royal Air Force and Royal Navy*. Volume 2. Chapter 105.

Nunneley, S. A., Dowd, P. J., Myhre, L. G., Stribley, R. F. (1978). Physiological and Psychological Effects of Heat Stress Simulating Cockpit Conditions. *Aviation, Space and Environmental Medicine*, 49(6), June 1978, pp. 763–67.

Pavia, R. V., and Edwards, D. H. (1977). *R.A.N. Sea King Cabin Environmentment Survey Part 1: Measurement of Vibration and Noise*. Mech. Eng. Note 366. July 1977. Melbourne: Aeronautical Research Laboratories.

RAAF Aircraft Research and Development Unit (1969). *Macchi Aircraft—Investigation into the Deficiencies of the Macchi Airconditioning System*. Report No. 1589, Parts 1 and 2, March 1969. Laverton: Royal Australian Air Force. Restricted.

RAAF Aircraft Research and Development Unit (1978). *CT4A Airtrainer Aircraft Cockpit Ventilation System*. July 1978. Edinburgh: Royal Australian Airforce.

RAAF Institute of Aviation Medicine (1976). *Nomad Thermal Environment Assessment*. April 1976. Point Cook: Royal Australian Air Force.

Rebbechi, B. (1977). *Estimation of Cabin Heat Loading in the Sea King Helicopter and Effectiveness of Possible Modifications to Improve Crew Thermal Environment*. Mech. Eng. Note 367. Melbourne: Aeronautical Research Laboratories.

Rebbechi, B. (1979). *An Analysis of Thermal Balance in the Cooled Cabin of a Sea King Helicopter*. Mech. Eng. Note 378. Melbourne: Aeronautical Research Laboratories.

Rebbechi, B., and Edwards, D. H. (1979). *RAN Sea King Environment Survey Part 2: Measurement of Temperature and Humidity*. Mech. Eng. Note 377. Nov. 1979. Melbourne: Aeronautical Research Laboratories.

Robeson, K. A., and Downie, R. J. (1978). *Personal Cooling in Industry*. Tech. Rep. No. TR 18. Highett, Victoria: Commonwealth Scientific and Industrial Research Organisation.

White, G. R. (1978). Private communication with the author.

APPENDIX 1

Initial Estimate of Sea King Cabin Cooling Requirements for a Vapour Cycle Cooling System

The external environment is taken to be $T_a = 43°C$, humidity ratio 0·021 kg moisture/kg dry air (37% relative humidity). With a vapour cycle cooling system, cabin air is recirculated, a small inflow of outside air being required for ventilation purposes only. Designating ventilation airflow to be 0·045 kg/s, and recirculated air leaving the cooling unit evaporator to be saturated, at 12°C (moisture content 0·009 kg moisture/kg dry air) then, assuming a ratio of recirculated air to ventilation air of 15 : 1, the general cabin air moisture content will be 0·010 kg moisture/kg dry air, and the cooling required to condense moisture in the ventilation air is

$$Q_l = m_f h_{fg} \delta_r, \tag{A1}$$

where Q_l = condensate cooling load (kW),

m_f = ventilation air mass flow (kg/s),

h_{fg} = latent heat of condensation = 2454 kJ/kg,

δ_r = required reduction in humidity ratio (= 0·012 in this case).

Then $Q_l = 1{\cdot}32$ kW, and from Equation (4),

$$Q_c = 0{\cdot}215(43 - T_c) + 1{\cdot}32 + Q_i + Q_{en}, \tag{A2}$$

and as $Q_{en} = 0{\cdot}98$ kW,

$Q_i = Q_s + Q_m + Q_e$,

$Q_s = 2{\cdot}0$ kW,

$Q_m = 0{\cdot}5$ kW,

$Q_e = 0{\cdot}5$ to $3{\cdot}0$ kW,

then $Q_i = 3{\cdot}0$ to $5{\cdot}5$ kW.

Thus, if $Q_e = 0{\cdot}5$,

$$Q_c = 14{\cdot}55 - 0{\cdot}215 T_c,$$

or, if $Q_e = 3{\cdot}0$,

$$Q_c = 17{\cdot}02 - 0{\cdot}215 T_c.$$

Then, as cabin moisture content is 0·010 kg moisture/kg dry air, and taking the cockpit black globe temperature to be $T_g = T_c + 6{\cdot}0$, and calculating cockpit WBGT according to Equation (1), Figure 2 can be drawn.

APPENDIX 2

Test Results

TABLE A1

Date: Feb. 1, 1979

Test: 2 hr ground run

Aircraft orientated at 300°

Time (hours)	1322	1351	1420	1435	1500	1530	1600
Thermocouple Number			→ Start Cooling Unit				
	Temperature °C						
1	29·2	29·4	88·7	90·4	91·3	89·7	90·1
2	28·9	29·1	8·2	8·4	9·1	7·5	8·1
3	29·1	29·5	5·6	4·9	4·5	3·2	2·5
4	29·9	30·2	83·7	84·1	83·9	83·1	81·2
5	29·8	30·1	57·5	56·5	55·9	55·1	54·8
6	25·9	25·9	30·0	29·2	29·4	28·2	28·2
7	30·3	30·6	30·1	29·1	30·7	29·1	28·9
8	30·6	30·8	25·1	23·1	22·2	21·1	20·9
9	26·7	27·3	20·4	19·4	18·3	17·3	17·1
10	31·2	30·4	11·5	11·8	11·3	10·1	10·4
11	39·8	43·3	33·0	29·9	27·5	21·5	21·0
12	32·3	34·9	22·2	20·4	19·9	19·2	18·4
13	32·8	33·6	31·8	29·6	28·3	27·8	26·3
14	31·6	32·2	25·0	23·0	22·2	21·2	21·2
15	31·1	31·6	25·3	23·7	22·5	21·4	21·3
16	31·4	31·9	24·6	22·9	21·9	21·0	21·2
17	27·0	27·9	22·4	20·1	19·1	18·3	18·1
18	30·0	30·1	29·0	28·5	29·6	28·9	27·6
P_{h1} (kPa)			1410	1410	1430	1380	1380
P_{h2} (kPa)			1480	1480	1480	1410	1410
P_{l1} (kPa)			220	207	207	193	193
P_{l2} (kPa)			231	220	214	200	200
Motor amps 1			18·0	18·0	17·5	17·0	17·0
Motor amps 2			19·0	18·5	18·0	17·5	17·5
Cloud cover			nil	nil	nil	nil	nil
Ground wind speed (kn)	4	4	10	10	14	14	14
Wind direction	040	040	040	040	050	040	040
Ground humidity (%)	47	47	45	45	45	45	45
Ground dry bulb (°C)	29	29	29	29	29	29	29
Total condensate (litre)	nil	nil	nil	nil		1·25	2·1
Sling psychrometer measurements							
Cabin dry bulb (°C)		32·5	25			21·8	20·6
Cabin wet bulb (°C)		25	18·3			14·4	14·4
Humidity (%)		55	52			44	48
Cabin moisture content		0·017	0·0105			0·0072	0·0075
Evap. outlet air moisture content					0·0074		0·007

TABLE A2

Date: Feb. 2, 1979

Test: Last Flight

Time hours	1140	1150	1206	1225	1250	1300	1320	1340
Thermocouple			→ Start Cooling Unit					
Number				Temperature °C				
1	26·3	26·6	86·4	86·8	85·7	85·5	85·3	84·9
2	24·9	25·0	9·6	9·1	7·6	8·1	7·7	7·0
3	26·7	27·2	6·7	10·5	5·1	4·5	3·8	4·0
4	26·6	27·1	81·7	87·5	83·5	81·7	81·1	81·8
5	27·4	27·2	52·9	52·6	52·7	52·4	52·1	51·6
6	23·1	22·9	28·1	27·3	27·6	27·6	27·3	26·9
7	30·5	30·1	33·6	29·3	33·5	35·0	33·2	33·4
8	28·9	30·3	26·4	23·9	23·6	23·8	23·6	22·9
9	24·9	25·1	20·3	19·9	18·7	18·6	18·2	18·4
10	26·6	29·3	11·9	12·0	11·3	11·2	11·3	10·1
11	43·7	43·2	27·8	26·7	28·3	29·1	28·6	27·6
12	29·8	30·5	22·6	22·9	21·8	21·4	21·8	20·2
13	30·9	31·7	28·3	29·0	25·6	27·2	25·3	30·3
14	29·6	30·7	27·9	25·1	23·1	23·0	22·9	22·6
15	29·9	30·3	26·5	26·2	22·8	23·3	24·0	24·3
16	30·9	31·0	29·3	26·8	25·7	25·6	25·5	24·9
17	25·6	26·3	20·9	19·4	18·6	17·7	19·0	18·3
18	28·6	28·9	23·6	23·0	25·2	26·1	25·8	23·2
P_{h1} (kPa)			1240	1240	1380	1380	1310	1310
P_{h2} (kPa)			1380	1380	1240	1310	1310	1380
P_{l1} (kPa)			220	207	214	220	207	200
P_{l2} (kPa)			241	234	227	234	227	220
Motor amps 1			17·0	17·5	17·0	17·8	17·5	17·0
Motor amps 2			18·5	18·2	18·0	18·0	18·0	18·0
Cloud cover			nil	nil	nil	nil	nil	nil
Ground wind (kn)								
Wind direction								
Ground humidity (%)	42		40					
Ground dry bulb (°C)	27		28					
Total condensate (litre)					1·1			
Sling psychrometer measurements								
Cabin dry bulb (°C)	29·5		24·5			23	22	
Cabin wet bulb (°C)	22·2		17·8			16·7	15·6	
Humidity (%)	53		52			52	50	
Cabin moisture content	0·014		0·010			0·0093	0·0084	
Evap. outlet air moisture content						0·0074		

TABLE A2 (Continued)

Time hours	1420	1430	1445
Thermocouple Number	Temperature °C		
1	88·1	87·4	88·2
2	8·6	8·7	9·8
3	5·7	5·4	6·6
4	85·0	82·1	85·3
5	54·9	55·1	54·9
6	27·6	28·7	29·3
7	36·9	36·4	35·4
8	24·1	24·6	25·0
9	18·5	19·2	20·0
10	11·0	10·7	12·1
11	26·9	27·1	25·8
12	21·9	21·7	22·1
13	28·2	28·6	27·9
14	26·2	26·8	26·9
15	25·5	25·7	25·7
16	28·0	29·1	28·6
17	19·1	19·3	19·2
18	28·9	26·1	27·2
P_{h1} (kPa)	1380	1340	1380
P_{h2} (kPa)	1450	1380	1450
P_{l1} (kPa)	214	214	227
P_{l2} (kPa)	227	227	248
Motor amps 1	17·5	18·0	18·0
Motor amps 2	18·0	18·2	19·0
Cloud cover	nil	nil	nil
Ground humidity (%)			46
Ground dry bulb (°C)			30
Total condensate (litre)	2·45		
Sling psychrometer measurements			
Cabin dry bulb (°C)	22·5	24·5	23·5
Cabin wet bulb (°C)	16·6	17·2	17·8
Humidity (%)	54	48	57
Moisture content	0·0094	0·0094	0·0103

TABLE A3

Date: Feb. 6, 1979

Test: Ground run

Aircraft orientated at 300°

Time hours	1400	1415	1430	1445	1500	1530	1600
Thermocouple Number		→ Start Cooling Unit					
				Temperature °C			
1	23·8	81·2	82·2	83·1	83·3	80·4	79·8
2	22·0	3·3	2·3	2·4	3·4	2·5	2·1
3	22·8	1·4	2·1	1·2	2·8	2·9	2·5
4	24·1	78·7	80·5	80·7	81·0	80·7	80·4
5	24·4	47·5	48·0	48·4	48·5	46·6	46·2
6	20·6	22·5	23·3	23·9	23·9	23·2	23·0
7	24·9	23·7	24·1	23·3	24·3	23·6	24·3
8	24·1	19·8	17·0	16·4	17·0	16·3	16·6
9	20·7	14·8	12·6	12·3	12 6	12·3	12·3
10	22·9	8·0	6·6	5·8	6·3	5·5	5·7
11	32·9	23·5	20·0	21·0	23·1	20·3	19·1
12	27·5	18·3	15·9	16·9	19·1	19·6	19·8
13	25·6	22·5	21·2	20·7	22·5	22·1	22·3
14	24·9	19·9	17·2	17·5	18·3	17·2	17·9
15	24·6	20·1	18·2	17·8	17·9	17·2	17·2
16	25·6	18·7	16·9	17·2	17·5	16·4	17·2
17	20·8	16·3	14·6	14·0	14·1	13·5	13·3
18	22·8	23·6	22·1	23·4	22·9	22·7	22·6
P_{h1} (kPa)		1210	1140	1170	1170	1140	1170
P_{h2} (kPa)		1210	1170	1210	1210	1170	1170
P_{l1} (kPa)		165	152	159	159	159	152
P_{l2} (kPa)		172	159	159	159	159	159
Motor amps 1		16·5	16·0	16·5	16·5	16·0	16·0
Motor amps 2		17·0	16·5	17·0	17·0	17·0	17·0
Cloud cover	light	light	light	light	light	light	light
Ground wind speed (kn)	8				5		6
Wind direction	100				100		80
Ground humidity (%)	50				53		53
Ground dry bulb (°C)	24				23		23
Total condensate (litre)		nil		0·25	0·56	1·18	1·65
Sling psychrometer measurements							
Cabin dry bulb (°C)		18			16·5	15	16
Cabin wet bulb (°C)		13·3			11·7	11·7	11·7
Humidity (%)		59			55	66	58
Moisture content		0·0076			0·0065	0·0072	0·0066

TABLE A4

Date: Feb. 7, 1979

Test: Ground run in hanger

Time hours	1200	1215	1230	1245	1300	1330	1400
Thermocouple Number		→ Start Cooling Unit					
			Temperature °C				
1	20·2	26·9	27·9	28·4	28·9	28·5	29·6
2	19·1	20·5	20·6	22·3	22·3	21·9	22·3
3	19·9	3·2	9·0	8·4	8·2	8·5	8·4
4	20·6	75·8	80·9	80·6	80·7	80·8	81·4
5	27·0	37·4	39·5	39·5	39·8	39·6	40·7
6	19·6	21·6	22·2	22·2	22·6	22·4	22·9
7	22·6	23·6	25·0	25·6	25·3	25·6	26·4
8	21·8	19·6	18·2	17·2	17·3	17·0	17·4
9	19·6	15·8	14·8	14·4	14·2	13·9	13·9
10	21·5	12·8	8·8	8·4	8·5	9·5	8·6
11	25·4	19·2	17·4	16·5	16·3	16·2	16·3
12	23·2	18·4	17·0	16·2	16·0	15·9	16·0
13	23·2	22·3	21·6	21·0	21·3	20·6	21·8
14	22·7	19·5	18·0	17·3	17·0	17·0	17·0
15	22·5	19·8	18·2	17·3	17·2	16·9	17·0
16	22·8	19·1	17·5	16·9	16·7	16·6	16·8
17	20·5	17·0	15·6	14·9	14·5	14·4	14·4
18	23·6	23·5	24·6	24·9	24·6	25·3	25·3
P_{h1} (kPa)		1030	1065	1100	1100	1100	1100
P_{h2} (kPa)							
P_{l1} (kPa)		165	193	186	186	186	186
P_{l2} (kPa)							
Motor current 1		16	16·2		16·1	16	16·1
Motor current 2		10	10·0		10	10	10
Ground humidity (%)							44
Ground dry bulb (°C)							25
Total condensate (litre)			0·51	0·53		0·79	0·99
Sling psychrometer measurement							
Cabin dry bulb (°C)		22·5	16·5	16·0		16·0	16·5
Cabin wet bulb (°C)		18·3	13·9	13·3		13·3	13·9
Humidity %		66	73	74		74	73
Moisture content		0·0114	0·0087	0·0084		0·0084	0·0087
Evap. outlet air moisture content						0·0078	0·0078

TABLE A5

Date: Feb. 7, 1979

Test: Ground run in full solar radiation

Aircraft orientated at 300°

Time hours	1420	1445	1500	1530	1600
Thermocouple Number		→ Start Cooling Unit Temperature °C			
1	30·6	29·8	30·0	30·3	29·9
2	17·6	23·7	24·2	25·0	25·4
3	22·1	10·4	11·4	11·1	11·1
4	35·1	82·2	83·3	82·7	82·2
5	31·1	40·9	41·8	42·0	41·8
6	25·5	23·7	23·9	24·2	24·2
7	31·0	25·4	26·2	26·2	26·5
8	21·1	21·0	21·8	22·3	23·0
9	17·7	16·7	17·1	17·4	18·0
10	18·2	11·0	11·4	11·6	12·5
11	41·2	33·7	34·2	35·3	35·0
12	27·4	22·5	22·6	23·3	25·0
13	25·1	25·9	26·4	27·0	27·6
14	22·1	22·3	22·9	23·7	24·2
15	21·0	21·3	22·0	22·7	23·1
16	22·6	22·1	22·8	23·6	24·0
17	17·3	17·6	18·0	18·7	19·0
18	25·9	25·3	25·3	26·4	26·1
P_{h1} (kPa)		1100	1140	1140	1170
P_{h2} (kPa)					
P_{l1} (kPa)		203	214	214	217
P_{l2} (kPa)					
Motor Amps 1		17	17	17	17·2
Motor Amps 2		10	10	10	10
Cloud cover	nil	nil	nil	nil	nil
Ground wind speed (kn)	6	3	3	3	4
Wind direction	120		140		100
Ground humidity (%)	44		44		47
Ground dry bulb (°C)	25		25		25
Total condensate (litre)	nil	nil	nil	nil	nil
Sling psychrometer measurements					
Cabin dry bulb (°C)	22	22	22	22·5	23·5
Cabin wet bulb (°C)	17·2	17·2	17·8	17·8	18·3
Cabin humidity (%)	62	62	66	63	60
Cabin moisture content	0·0103	0·0103	0·0110	0·0108	0·0110
Evap. outlet moisture content		0·0094	0·0092	0·0095	0·0095

APPENDIX 3

Airflows and Pressure Losses through the Cooling System

The airflows through the cooling unit are as follows:

(*a*) condenser airflow: 0·790 kg/s;

(*b*) condenser face velocity: 5·20 m/s;

(*c*) evaporator airflow (all tests except 7 February 1979): 0·683 kg/s;

(*d*) evaporator airflow (tests on 7 February 1979): 0·514 kg/s.

The air pressures through the cooling unit are, for all tests other than 7 February 1979:

evaporator fan pressure rise, 861 Pa;

evaporator matrix pressure drop, 109 Pa

pressure at inlet to ducting (evaporator fan outlet), 752 Pa;

condenser fan pressure rise, 403 Pa;

pressure drop across condenser matrix, 363 Pa.

APPENDIX 4

Cooling Effect Calculations

The (sensible heat) cooling effect of the airconditioning unit

$$= (T_8 - T_{10})m_e C_p - PE_{out} - KE_{out}, \tag{A3}$$

where T_8 = dry bulb air temperature at inlet to evaporator (°C),

T_{10} = dry bulb air temperature at outlet from evaporator fan (°C),

m_e = mass flow of air through evaporator (kg/s),

C_p = specific heat of air = 1·012 kJ/kg °C,

PE_{out} = potential energy of air at outlet from fan (kW),

KE_{out} = kinetic energy of air at outlet from fan (kW).

For all tests other than 7 February 1979, fan outlet pressure = 752 Pa, outlet velocity = 18·3 m/s, and mass flow = 0·683 kg/s,

PE_{out} = (fan outlet pressure (Pa))(mass flow (kg/s))/(density (kg/m³)),

then

$PE_{out} = 425$ W.

$KE_{out} = 0{\cdot}5$(mass flow (kg/s))(velocity (m/s))²,

hence

$KE_{out} = 114$ W.

For tests on 7 February 1979, fan outlet pressure = 572 Pa, fan outlet velocity = 13·8 m/s, and mass flow = 0·515 kg/s.

Hence, $PE_{out} = 245$ W,

$KE_{out} = 49$ W.

APPENDIX 5

Heat Balance for Parked Aircraft

The derivations of the basic equations for the parked aircraft case are given by Rebbechi (1979). The general heat balance equation (5) applies to the parked aircraft, with doors and windows closed. This equation can be brought to the form

$$Q_c = (T_a - T_c)[(0{\cdot}0028 + 0{\cdot}496h_c)/(0{\cdot}018 + h_c) + C_p m_f] + 0{\cdot}036/(0{\cdot}018 + h_c) + 2{\cdot}49, \qquad \text{(A4)}$$

h_c being a function of ground wind speed as given in Figure A1.

This equation is graphically presented in Figure 30; it is for an aircraft parked in full solar radiation, no occupants, engine and avionics not operating, and cabin ventilation airflow (m_f) 0·045 kg/s.

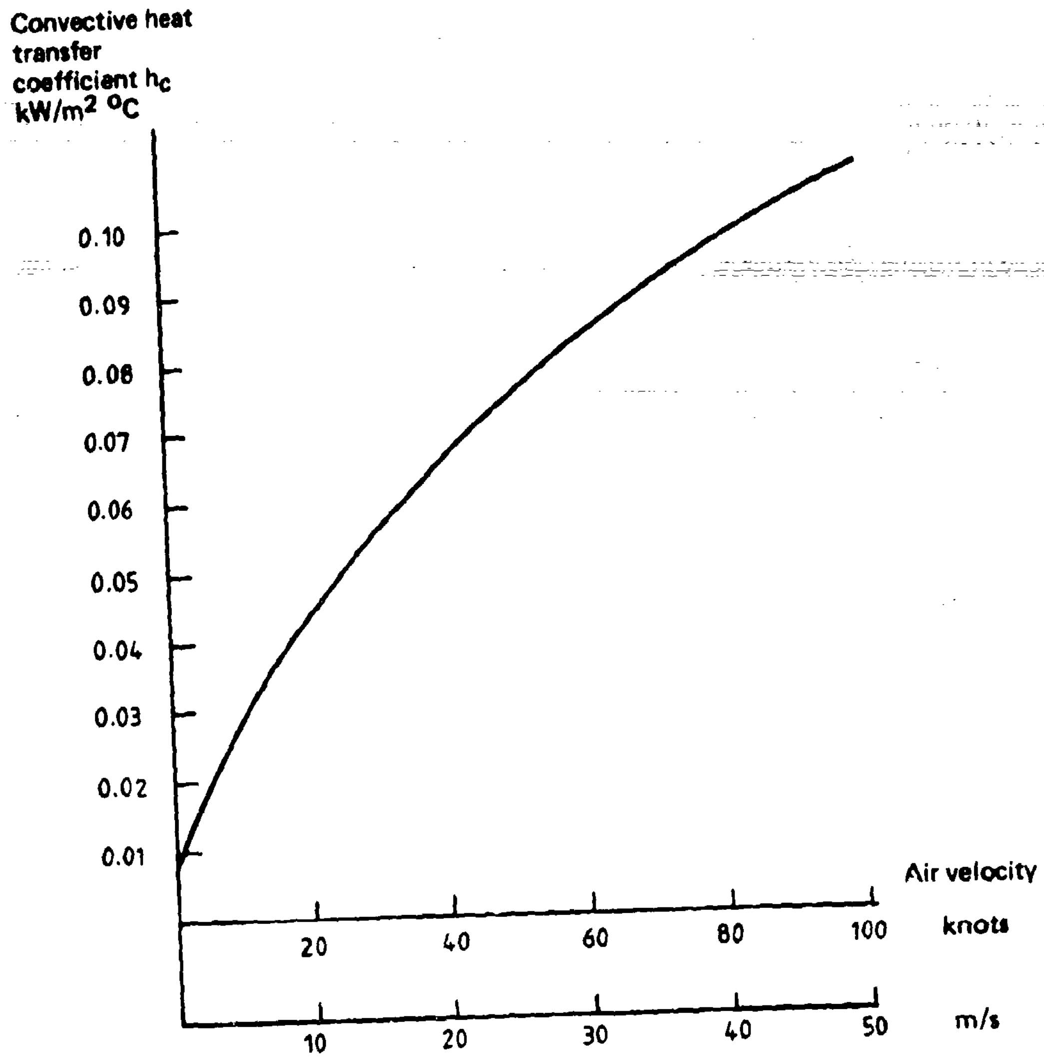


FIG. A1. CONVECTIVE HEAT TRANSFER COEFFICIENT VS. AIR VELOCITY.

DISTRIBUTION

	Copy No.
AUSTRALIAN	
Department of Defence	
Central Office	
Chief Defence Scientist	1
Deputy Chief Defence Scientist	2
Superintendent, Science and Technology Programs	3
Australian Defence Scientific and Technical Representative (UK)	—
Counsellor, Defence Science (USA)	—
Assistant Attache Defence Research and Development (USA)	4–5
Joint Intelligence Organisation	6
Defence Library	7
Document Exchange Centre, D.I.S.B.	8–24
Director of Program Management (Scientific), (Att. Mr J. G. Garlick)	25
Aeronautical Research Laboratories	
Chief Superintendent	26
Superintendent — Mechanical Engineering Division	27
Divisional File — Mechanical Engineering	28
Author: B. Rebbechi	29
F. W. Hooton	30
R. E. Pavia	31
D. C. Collis	32
A. Ross	33
P. A. J. Clark	34
Materials Research Laboratories	
Library	35
Dr J. McRae	36
Defence Research Centre, Salisbury	
Library	37
Navy Office	
Naval Scientific Adviser	38
Flag Officer Commanding Her Majesty's Australian Fleet	39
The Flag Officer Naval Support Command	40
The Australian Naval Representative (UK)	41
The Australian Naval Attache (USA)	42
Director of Naval Aviation Policy	43–44
Director of Naval Aircraft Engineering	45
Directorate of Naval Aircraft Engineering, Mr L. Gillard	46–48
Superintendent of Aircraft Maintenance and Repair	49–50
C.O. Naval Aircraft Station, Nowra	51
C.O. 817 Squadron, NAS Nowra	52–53
OIC AMAFTU, NAS Nowra	54–55
RAN Research Laboratory	56

Army Office

Army Scientific Adviser	57
Library, Engineering	58

Air Force Office

Air Force Scientific Adviser	59
Aircraft Research and Development Unit	60
Aircraft Research and Development Unit, Library	61
Technical Division Library	62
SENGSO Headquarters Support Command	63
D G. Air Eng.-AF	64
Institute of Aviation Medicine, Point Cook	65

Department of Productivity

Government Aircraft Factories

Library	66

Department of Transport

Director General/Library	67
Airworthiness Group, Mr K. O'Brien	68

Statutory and State Authorities and Industry

CSIRO Central Library	69
CSIRO Mechanical Engineering Division, Chief	70
Trans Australian Airlines, Library	71
Qantas, Library	72
Ansett Airlines of Australia,	
Technical Manager	73
Library	74
Commonwealth Aircraft Corporation:	
Manager	75
Manager of Engineering	76
Mr D. Beenham	77
Hawker de Havilland Pty. Ltd.:	
Librarian, Bankstown	78
Manager, Lidcombe	79
Normalair Garrett Ltd.	80
Institution of Engineers, Australia, Library	81
Rolls Royce of Australia Pty. Ltd.	82

Universities and Colleges

Adelaide	Barr Smith Library	83
Deakin	Library	84
Flinders	Library	85
James Cook	Library	86
Latrobe	Library	87
Melbourne	Engineering Library	88
Monash	Hargrave Library	89
Newcastle	Library	90
New South Wales	Physical Sciences Library	91
Queensland	Library	92
Sydney	Engineering Library	93
	Professor G. A. Bird	94
Tasmania	Engineering Library	95
West. Australia	Library	96
RMIT	Library	97
	Mr H. Millicer	98

CANADA

NRC, National Aeronautics Establishment, Library	99
NRC, Division of Mechanical Engineering, Director	100

NEW ZEALAND	
Defence Scientific Establishment, Library	101
FRANCE	
AGARD, Library	102
ONERA, Library	103
Service de Documentation, Technique de l'Aeronautique	104
INDIA	
National Aeronautical Laboratory, Director	105
Institute of Aviation Medicine, Indian Air Force	106
UNITED KINGDOM	
Aeronautical Research Council, N.P.L., Secretary	107
CAARC NPL, Secretary	108
Royal Aircraft Establishment:	
Library, Farnborough	109
Flight Systems Dept., G. R. Allen	110
Flight Systems Dept., E. J. Lovesey	111
Library, Bedford	112
Royal Air Force Institute of Aviation Medicine, Farnborough:	
Library	113
Dr J. R. Allen	114
M. H. Harrison	115
Aircraft and Armament Experimental Establishment	116
National Engineering Laboratories, Superintendent	117
Rolls Royce (1971) Ltd., Aeronautics Division, Chief Librarian	118
Normalair Garrett Ltd., G. Giles	119
Westland Helicopters Ltd., Asst. Chief Designer Sea King, E. Roadnight	120
Westland Helicopters Ltd., Chief Engineer, D. Berrington	121
British Aircraft Corporation (Holdings) Ltd. Military Aircraft	122
British Aerospace Aircraft Group:	
Manchester Division	123
Kingston-Brough Division	124
Headquarters, Kingston-Upon-Thames	125
Head of Aircraft Department for Royal Navy	126
Naval Attache, British High Commission (Canberra)	127
Universities and Colleges	
Southampton — Library	128
M. J. Griffin	129
UNITED STATES OF AMERICA	
NASA Scientific and Technical Information Facility	130
United States Army Aviation Engineering Flight Activity:	
Edwards Air Force Base, Library	131
Edwards Air Force Base, E. J. Laing	132
United States Army Aeronautical Research Laboratory	133
USAF School of Aerospace Medicine:	
Library	134
Environmental Sciences Division, S. A. Nunneley	135
United States Naval Air Test Centre	136
Garrett Corporation	137
Hamilton Standard	138
Fairchild, Stratos Division	139
J. B. Systems, Inc.	140
Boeing Vertol Company	141